SLURRY PIPELINE MANUAL
Design and Construction

Editor
W.H.W. Husband

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Prepared for
Transportation Development Centre of
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SLURRY PIPELINE MANUAL

Design and Construction

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17. Abstract

Results of more than fifteen years of Canadian research expertise on slurry pipelines have been consolidated into a comprehensive and practical design and construction manual. The manual is directed towards undergraduate and practising engineers engaged in the planning, design, evaluation and regulation of slurry pipelines and aims to achieve maximum technology transfer in the field. Seventeen chapters cover the full range of subject matter from historical development of slurry pipelines through conventional liquids pipeline design and slurry preparation, flow principles, pipeline design, pumping, testing, dewatering, environmental aspects, etc., all the way through to standards, costs, regulatory aspects and research and development needs.

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17 Résumé

Ce manuel sur la conception et la réalisation de conduites pour le transport de matériaux entraînés hydrauliquement réunit les résultats d'une quinzaine d'années de recherche et d'expérimentation canadiennes dans ce domaine. Il est destiné aux ingénieurs, nouveaux et chevronnés, chargés de planifier, étudier, évaluer et réglementer ce type de transport, mettant à leur disposition toutes les connaissances accumulées. Il comporte dix-sept chapitres traitant de ce sujet sous tous ses aspects: préparation des suspensions, régulation des débits, étude des canalisations et des installations de pompage, séparation en fin de ligne, impact sur l'environnement, essais, normes, études des coûts, réglementation, recherche et développement, ainsi qu'un historique complet, sans oublier le sujet des canalisations hydrauliques classiques.

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PREFACE

This publication is the first edition of a comprehensive manual on the design and construction of slurry pipelines. Transport Canada intends that subsequent up-dated editions of the manual will be published from time to time to incorporate the latest technology emerging from long term research and development efforts in Canada and other countries.

Preparation of this edition of the manual was initiated by Transport Canada's Transportation Development Centre (TDC) and sponsored almost entirely by funding provided by the Interdepartmental Panel on Energy R&D (PERD) and administered by Transport Canada.

Transport Canada has supported research and development of slurry pipelines in Canada for more than 20 years. The manual is a culmination of the results and has been prepared to foster the use of slurry pipelines in industry as an economical alternative for transporting solid materials such as minerals, coal, intermediate products and wastes, such as mill tailings.

Successful use of a new technology requires good basic understanding of it by people who are involved in examining and assessing industrial concepts and proposals which potentially could utilize that technology. Usually these people have engineering backgrounds. Consequently, this manual is oriented toward project and design engineers, especially engineers who are considering slurry pipelining for the first time. For those engineers who are already familiar with the field, Chapters 3, 7, 8, 10 and 17 cover the main topics of interest to them.

Complete derivations of the equations and details of the calculations used in the manual are on file at the Saskatchewan Research Council. Also, the Council has available a collection of over 4000 papers published in the technical literature on slurry pipelines.

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SYMBOLS AND UNITS IN HYDRAULIC TRANSPORT OF SOLIDS IN PIPES

A	=	cross sectional area of pipe	m^2
C_D	=	drag coefficient $C_D = 2\tau_o g/\rho V^2$	-
C_v	=	concentration by volume (fraction)	-
C_w	=	concentration by weight (fraction)	-
d	=	particle diameter	m
D	=	internal pipe diameter	m
f	=	friction factor (D'Arcy friction factor = 4 x Fanning friction factor)	-
g	=	gravitational constant	m/s^2
H	=	total head	m
He	=	Hedstrom number $\rho D^2 \tau_y / \mu_p^2$	-
ΔH	=	total head loss	m
i	=	head loss gradient (units of conveying fluid)	m/m
j	=	head loss gradient (units of mixture)	m/m
J	=	pressure gradient $(\Delta P/L)$	Pa/m
k	=	mean size of pipe roughness element	m
K	=	consistency index (power law)	$Pa \cdot s^{-n}$
M	=	mass flow rate	kg/s
n	=	exponent (power law)	-
p	=	pressure	Pa
Δp	=	pressure drop	Pa
Q	=	volumetric flow rate	m^3/s
Re	=	Reynolds number $DV\rho/\mu_p$	-
Re_p	=	Reynolds number of particle $dV_t \rho_s/\mu_p$	-
s	=	relative density, density ratio of solids to carrier fluid	-
S	=	surface area per unit length of pipe	m^2
v_*	=	friction velocity = $(\tau_o/\rho_f)^{0.5}$	m/s
V	=	velocity	m/s
V_c	=	deposit velocity	m/s
V_t	=	terminal settling velocity of solids	m/s
V_t'	=	hindered terminal settling velocity of solids	m/s
W	=	power	W
x_i	=	mass fraction	-
z	=	rectangular coordinate in downstream direction	m
$\dot{\gamma}$	=	rate of shear	s^{-1}
μ	=	dynamic viscosity (shear stress/shear rate)	$Pa \cdot s$
μ_p	=	plastic viscosity (Bingham fluid)	$Pa \cdot s$
υ	=	kinematic viscosity μ/ρ	m^2/s
ρ	=	density	kg/m^3
τ	=	shear stress	N/m^2
τ_y	=	yield stress (Bingham fluid)	N/m^2
ω	=	angular velocity	rad/s

Subscripts

d	=	delivered	e.g. C_{vd}
f	=	fluid	e.g. V_f
m	=	mixture	e.g. Q_m
o	=	pipewall	e.g. τ_o
s	=	solid	e.g. ρ_s
r	=	in-situ	e.g. C_{vr}
1	=	upper layer	e.g. V_1
2	=	lower layer	e.g. V_2
12	=	interface value	e.g. V_{12}

1. INTRODUCTION

by

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1.1 INCREASING USE OF PIPELINES

Pipelines unquestionably are the most economical method of transporting large quantities of domestic water, oil, natural gas, and other fluids. In the United States there are more than 330,000 km of oil pipelines, 380,000 km of interstate gas pipelines and 1,500,000 km of water pipelines (Ref. 1). Interprovincial Pipelines Ltd. and Trans Canada Ltd. move oil and gas through more than 20,000 km of pipelines from Western Canada to Central and Eastern Canada. In total, there are more than 40,000 km of oil pipelines and 175,000 km of gas pipelines in Canada.

Although mixtures of solids and liquids have been transported in flumes or pipes for hundreds of years, until recently the majority of the applications have been in-plant transfers over relatively short distances. Only since 1957 has the slurry pipeline method been used to transport solids on a large scale over considerable distances, such as the 180 km coal pipeline which operated between Cadiz and Cleveland. During a 20-year period more than 1,500 km of pipeline capable of carrying 30 million tonnes of solids per year have been built (Ref. 2).

The transport of solid materials in pipes is a well established method of moving materials from place to place in Canada. The mining industry uses dredges to remove overburden and to process placer gold deposits. Also, the industry transports tailings through pipelines to disposal ponds or to backfill sites in mines. The construction industry uses dredges to recover and process sands and gravels. This industry also uses pumps and pipelines to transport sands, gravel, and concrete to points of placement in projects such as dykes, embankments, dams and other large construction projects. Chemical, petroleum, metallurgical, pulp and paper, and other industrial plants use pipelines to transport raw materials, materials in process and finished products in large quantities through their facilities.

Because of the advantages and economics of in-plant pipelines, designers continually have to cope with increasingly severe conditions and more complex slurries. For similar reasons, the designers will have to examine the potential for short, intermediate and long distance pipelines for moving materials like coal, mineral concentrates, mill tailings, and dense coal-water or coal-oil mixtures for electrical generating plants. As easily accessible ore bodies become depleted, as larger scale operations are required, and as environmental issues require better disposal of wastes, slurry pipelines will become increasingly attractive options.

1.2 CONCEPTION OF A SLURRY PIPELINE MANUAL

Transport Canada has supported research and development of the transport of solid materials through pipelines since the late 1960's. Initially the studies investigated two methods of pipeline transport: the transport of solids in capsules, and the transport of solids as a liquid-solid slurry. In recent years the research has concentrated on the slurry method, because most commercial interests are in this direction. The Transportation Development Centre (TDC) of Transport Canada, and its predecessor the Transportation Development Agency, directed the program through a series of contracts and grants to provincial research councils and universities. The main result of the program has been the establishment of the Slurry Pipeline Development Centre by the Saskatchewan Research Council (SRC) at Saskatoon. This Centre has operated since 1976 solely on a contractual basis with industry and governments.

In 1982 TDC decided the time had come to consolidate the work done on slurry pipeline research into a practical design manual for engineers engaged in the planning, design and evaluation of slurry pipelines in Canada. Such a manual would provide an up-to-date reference book on the subject. Preparation of the manual would result in the identification of areas of current uncertainty in the technology. Then, a rational review of these deficiencies could priorize them and develop an appropriate long-term development program for the slurry pipeline method of transporting solid materials.

TDC commissioned SRC to prepare this manual. The manual will be up-dated from time to time to incorporate the latest findings of the long-term development program in Canada and research in other countries. Thus, the manual will ensure maximum technology transfer.

1.3 OBJECTIVE

The main objective of this manual is to provide a practical design manual which can be used by engineers with varying degrees of interest in slurry pipeline applications. Some engineers with no experience in pipeline design require a general reference work which gives a simple outline of a slurry pipeline system, the main factors to consider in its design, a preliminary design method, and sufficient cost data to enable them to undertake a quick cost estimate of a potential application. Other engineers need a detailed reference work to assist them to prepare a thorough system design and an accurate cost estimate. Therefore this manual has been organized to provide a wide range of information and in a manner that an engineer can access the information in whatever depth he desires. Each chapter begins with a general discussion, proceeds to go into more and more detail, and finishes with a list of additional references. In some cases chapters have appendices which outline specific calculations and solutions.

1.4 ORGANIZATION OF THE MANUAL

The main chapters have been arranged in a sequence which parallels the phases which an engineer would go through if assigned, for the first time, the task of developing a slurry pipeline project. Chapter 3 sets the stage by outlining the subjects an engineer must consider in designing a relatively simple liquid pipeline. The design of such a pipeline follows conventional procedures and is well understood. Chapter 4 builds upon this background to outline very generally some slurry pipeline systems, how they fit into the industrial world, and the more complicated flow regimes which can occur within the pipelines. Chapter 5 discusses the preparation of the solids prior to entry of the pipeline. Coal is used as an example because there are coal pipelines in operation in various parts of the world. Chapter 6 reviews the pumps which charge the pipelines and operate at intermediate stations along the pipelines.

The principles of slurry flow in pipes are discussed in Chapter 7 and, because the theoretical treatment of such flow is very much in the development stage, different engineering solutions present in the technical literature are reviewed and example calculations are provided. In Chapter 8 the subjects an engineer must consider in designing a slurry pipeline are outlined. As the technical and economic factors vary considerably with the various applications of slurry pipelines, the design aspects are treated in a general manner and then, in appendices, are covered in more specific detail with sample calculations for three different types of slurry pipelines. In most cases, the solids must be recovered from the slurry at the terminus of a pipeline or pipeline system. Chapter 9 covers this operation using coal as an example.

If the preliminary design of a slurry pipeline indicates the desirability of proceeding further with the project, additional matters have to be considered. These items are covered in Chapters 10 to 16.

Preliminary designs are based on the best data available and affordable at the time. However, as slurry pipelining is still a developing method of transport, data applicable to specific proposed projects are scarce. In addition, as long slurry pipelines can be expensive and senior company executives prefer to minimize risks where new technology is involved, physical testing of the slurry to be transported is desirable. Chapter 10 addresses this aspect.

When the engineer is satisfied that the basic design of the pipeline is sound, consideration would then be given to the engineering standards, construction techniques, environmental concerns, planning and scheduling of construction, costs of the project, and regulatory requirements with which eventually a pipeline operation has to comply. Chapters 11 to 16 cover these subjects.

Finally, as a guide to future development of the technology, Chapter 17 outlines the areas in which further research and development is needed.

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2. HISTORICAL DEVELOPMENT OF SLURRY PIPELINES

by

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2.1 INTRODUCTION

The transportation of liquids and solids in the form of slurries has been going on in nature for eons in geological time. Rivers have moved mountains and reshaped continents, carrying boulders in their upper reaches and finally depositing gravels, sands, silts and clays in the oceans. Early man gradually developed primitive irrigation systems to move water under gravity flow and to drain wastes away from living areas. Eventually, early civilizations began to move water and sewage in quantity in pipes; the Roman aquaducts and sewers were early examples. Today, the quantities of fluids and solids moved through pipes are phenomenal. In the United Kingdom, alone, more than 5,000 million tonnes of water are pumped through pipes to users. This water is removed through a secondary system of sewers which handle in addition the enormous amounts of water and silts from storm runoff.

Commercial use of slurry transport in modern times began in the goldfields of California and Australia in the 1850's. Hydraulic elevators raised water and gold-bearing gravel to heights of 15 m (50 ft) for discharge into sluices. About the same time, suction dredging with centrifugal pumps was developed. Dredging was used initially to deepen waterways and later the method was used to reclaim land from the sea and to build artificial islands. One hundred and fifty examples of dredging have been summarized in a 1977 paper (Ref. 1). Some of these projects moved more than 100 million cubic metres of solids.

Long distance overland transport of materials in pipelines developed with the oil and gas industries. The first oil pipelines were built in the United States, a 100 km line in 1875 and a 180 km line in 1879. After more than 100 years of development, the United States now has over 300,000 km of large diameter oil pipelines. The sophistication, complexity, and efficiency of this method of transport is illustrated by the 2,500 km line from Houston to New York City. At any one time, there are up to 100 individual batches of oil enroute to about 200 delivery points. On the other hand, the size of the gas distribution system in the United States dwarfs that of oil; there are over 400,000 km of transmission lines, one million km of distribution mains, and 700,000 km of service lines.

2.2 PIPELINING OF COAL

With the obvious economic advantages of pipelining water, sewage, oil and gas, it was only natural that entrepreneurs investigated the transportation of other materials via pipelines. In 1851, a demonstration in London showed that a centrifugal water pump could pass relatively coarse solids through it. In 1860, centrifugal pumps had been developed to the point where they were used in hydraulic dredging to move large quantities of sand and gravel. In 1889, W.C. Andrews filed a U.S. patent for conveying finely ground coal as a water slurry for hundreds of miles. During World War I, G.G. Bell used a centrifugal pump to transport 100 mm lump coal from barges on the Thames through 600 metres of 200 mm diameter pipe to the electrical generating station at Hammersmith. The mixture, 50% coal by weight, moved at 1.2 m (4 ft) per second at a rate of 50 tonnes per hour.

In 1951, Consolidation Coal began a $2 million study on moving coal by pipeline. The work culminated in the construction of the now famous 175 km, 250 mm diameter, coal pipeline in Ohio from Cadiz to Cleveland. This pipeline operated successfully for six years and forced the railways to lower freight rates by a factor of two which eventually justified mothballing the pipeline.

The success of the Cadiz-Cleveland coal pipeline led to an even larger coal pipeline being constructed in 1970. The Black Mesa line today carries up to 4 million tonnes per year of coal a distance of 440 km from coal mines in Arizona to the Mohave power station in Nevada. Operational reliability is 99%.

The economic advantage of transporting coal through pipelines, together with the oil crisis of 1974, created a tremendous interest in this method in the United States. By 1982, six major coal pipelines were being planned to transport over 100 million tonnes of coal through 10,000 km of pipeline. The railways, faced with such a threat to their future expansion, have used their strong influence in Congress to block all attempts to repeal their right of eminent domain. This right essentially allows the railways to forbid a pipeline to cross under their right-of-way. No such right exists in Canada.

Recently, Consolidation Coal has capitalized on the development of using slurry pipelines to transport ores from underground mines. Although hydraulic mining of ores has been practiced for more than 100 years, this method used flumes and gravity flow to transport the ores and waste rock down slope. Beginning in 1977, hydraulic hoisting of coal from considerable depth in a mine was successfully developed at the Hanza coal mine in Germany. Consolidation Coal extended the concept to couple the hydraulic hoisting system directly to continuous miners in 1981. More than 1,000,000 tonnes of coal have been transported from the underground miners to the above-ground preparation plant at the Loveridge Mine in West Virginia. The reliability of the experimental system was 93% and there were no recordable accidents in the mine during a two-year test period.

2.3 PIPELINING OF MINERALS

Transportation of minerals through pipelines began in an unusual manner by moving soluble minerals as brines. A pipeline built in 1616 conveyed salt brines 31 km from Reichenhall to Traunstein in Bavaria. The line was rebuilt and extended around 1810 to over 100 km. Rock salt was dissolved, pumped through the line, and then recovered by evaporation.

The phosphate industry in Florida has been using hydraulic mining and transport of phosphate pebbles through pipelines since 1900. At present, there are more than 20 phosphate pipelines in Florida, transporting 30 million tonnes per year of phosphate rock up to 8 km at rates as high as 2,000 cubic metres per hour. Pebbles up to 150 mm in diameter are transported through pipelines as large as 500 mm in diameter.

During the period 1960 to 1970, steel production in the world expanded dramatically and iron ore shipments from under-developed countries increased from 40 to 240 million tonnes. As a consequence, a number of pipelines to transport iron ore or iron concentrate appeared. By 1980, the mining industry was moving about 30 million tonnes of iron ore per year through 650 km of pipeline.

Copper production also increased during the 1960-70 period. New mines in remote parts of the world used pipelines to move the copper concentrates to seaports or to more suitable locations for refining. Approximately 300 km of pipeline were constructed to move 2.5 million tonnes of concentrates per year.

2.4 PIPELINING OF CLAY AND LIMESTONE

Hydraulic mining of clay was developed as an early spinoff from hydraulic dredging. In Cornwall and Devon in the United Kingdom millions of tonnes per year of china clay are hydraulically mined, hoisted through pipes to washeries, and then pumped through pipes to refining and classifying processes. These in-plant lines typify the innumerable applications of slurry transfer through short lines in the refining and processing industries around the world. However, longer pipelines are used also in the china clay industry. In Georgia, U.S.A., an 8 km line began operation in 1959 and since then two other lines, 18 and 26 km long, have been put into service transporting china clay from mines to processing plants. Each line handles over 1 million tonnes per year of clay. In 1978, the industry began exporting china clay as a slurry in ships. An 18 km line in Cornwall conveys refined china clay to a seaport for this purpose.

Clay and limestone are mixed to make cement. A recent trend has been to move the raw materials to the location of use for processing and subsequent distribution of the finished cement. Pipelines not only offer an economical mode of transport but also allow the end product to be made near the consumer without visible disruption of built-up areas and reduce the radius of final distribution. In 1962, a 10 km limestone line was built in Trinidad by the British Rugby Portland Cement Co. Ltd. This led the company to construct a 92 km line in the United Kingdom to convey 1.5 million tonnes of limestone. Subsequently, limestone pipelines have been constructed in North and South America, the largest one being the 28 km Calaveras line in California.

2.5 PIPELINING OF MINERAL WASTE

In terms of throughput, the tonnage conveyed by mineral waste or tailings pipelines far exceeds that of any other type of slurry pipeline. Vast quantities of waste materials have to be disposed of by the refining and processing industries.

Although these pipelines are short, rarely exceeding 5 km, they are essential in the control of processing cost and for the protection of the environment. In the field of thermal power generation alone, in 1977 on a world-wide basis, more than 500 million tonnes of fly ash had to be moved through fly ash disposal lines from the boilers to the fly ash lagoons. In Canada, the tar sand companies pump 100 million tonnes per year of sand tailings as far as 7 km to disposal sites.

2.6 ADVANTAGES OF SLURRY PIPELINES

The advantages of the short distance, in-plant type of slurry pipeline are obvious to anyone connected with the refining and process manufacturing industries. The method is simple, efficient, automatic, economic, safe and firmly established all around the world. Consequently, this discussion will concentrate on longer slurry pipelines, those operating outside the plant gate.

The major criterion for comparing the slurry pipeline method to other methods of transportation for industrial materials is cost. Most criteria, such as safety and reliability, can be converted into costs which then may be summed to give an overall intermodal cost comparison, for instance, in terms of cents per tonne of material per kilometre moved. However, when comparing slurry pipelining to other forms of transportation, it becomes

meaningless to managements and financiers to discuss the economics in general terms. There are just too many variables involved which can cause generalizations to produce misleading results. Rather, one should base intermodal comparison on specific costs of specific applications. The factors which should be considered when making intermodal comparisons are:

a. economic advantages
   - high efficiency,
   - high reliability,
   - low inflation,
   - relatively strike immune.

b. geographical flexibility
   - all terrain,
   - processing plant location,
   - social considerations.

c. environmental protection
   - buried,
   - little land used,
   - social considerations.

d. safety
   - buried,
   - automated.

e. disadvantages
   - low turn down,
   - fixed input and output points,
   - water supply and disposal,
   - limitations to materials conveyed.
   - high capital, low variable costs.

The two biggest advantages of slurry pipelines are: a) an inherently high efficiency of transport which increases with volume and distance, and b) the long-term inflation protection characteristic of a capital intensive system. Wasp et al. (Ref. 2) demonstrated the former effect with coal transportation, as shown in Figure 2.1. Link (Ref. 3) has reported that approximately 70% of the unit cost of transporting a slurry is made up of capital-related or other fixed cost. About half the remainder is cost of power to operate the pumps, and only 15% of the total cost can be attributed to labour and operating costs which are subject to inflationary influences.

Slurry pipelines can be constructed through all kinds of terrain. Mountains, canyons and rivers do not pose insurmountable barriers and hence ore deposits in remote and inaccessible locations can be exploited without the construction of circuitous and more costly railways or long truck hauls. In short, slurry pipelines can be routed in the most direct way possible. They also permit minimizing employees required at remote mine sites, as processing plants can be located at existing communities on rail lines or at seaports.

Slurry pipelines cause very little environmental disruption. They are buried. In fact, the only environmental effect occurs along the narrow right-of-way during construction and for a short time thereafter. After appropriate revegetation, there is practically no evidence of the systems' existence. This absence of physical evidence contrasts vividly with the passage through communities of unit trains or trucks of alternative transport systems.

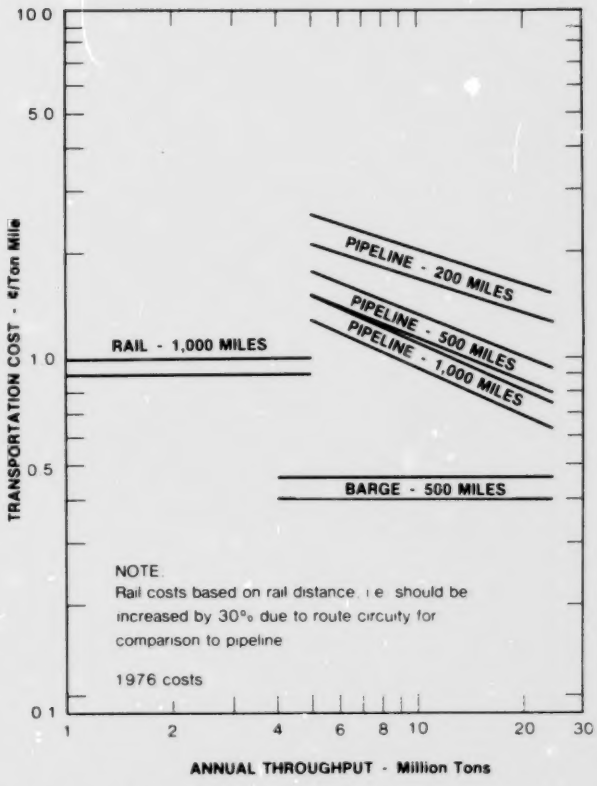

Figure 2.1 Slurry pipeline – coal transportation costs (by permission, from E.J. Wasp, J.P. Kenney and R.L. Gandhi, Trans Tech. Publications, Clausthal, 1977)

As slurry pipelines are buried, controlled automatically, and use water as a carrier fluid in most cases, the chances of accidents and injury to people are extremely low. In fact, a recent installation of slurry pipeline transport in a coal mine has shown that hazards due to dust, gases, haulage vehicles and moving equipment such as conveyors, are greatly reduced.

2.7 LIMITATIONS OF SLURRY PIPELINES

The main technical limitations to long distance slurry pipelines are:

a. low turn-down, i.e flowrates cannot be varied widely,
b. fixed entry and delivery points,
c. water supply,
d. water clean-up and disposal,
e. limitations to materials conveyed.

Because of the nature of the flow regime in slurry pipelines, the throughput of a line cannot be varied widely. A certain minimum flow velocity has to be maintained to keep these solids in suspension to avoid

blockage. On the other hand, the higher the velocity the greater the pumping power costs and the greater the erosion rates on the pipe walls. Thus, slurry pipelines usually have low turn-down ratios.

Compared to truck and rail transport, slurry pipelines have a very limited distribution capability. In most cases they transport material from its source to one designated delivery point. Once installed, the slurry pipeline cannot be relocated. Although intermittent delivery points can exist along a major line, these points usually have to be incorporated in the original design.

Water is the most common carrier fluid used in slurry pipelines. In some cases, its supply at the beginning of a pipeline may be scarce and in most cases it has to be separated from the slurry at the discharge point and treated before being disposed. Such limitations can add to the costs of operation.

There are limitations to the type of materials which can be transported through pipelines. The material has to be compatible with the carrier fluid and amenable to separation from the fluid at the pipeline terminal or somewhere in the subsequent processing or use of the material.

The high proportion of capital costs is a major economic limitation to long distance slurry pipelines. The "front end" costs make cash flow difficult in early years and make long term profit estimates dependent on risks of throughput not being high in early years of operation. The large capital costs, the perception of technological risk, and the potential for future changes in the supply and demand of a specific material to be transported, cause financial people to question the value of the mode relative to the higher cost, but better understood, and more flexible, modes such as railways and trucks.

2.8 SUMMARY

Hydraulic transport of solids through pipelines has been developed steadily since the adaptation of the centrifugal pump to slurries in the 1860's. As the world became more industrialized, pumps have become the second most common machine in use, being exceeded only in numbers by the electric motor. They are used for in-plant transfer of slurries in a wide range of industries:

a. thermal power plants,
b. chemical plants,
c. petroleum refineries,
d. pulp and paper mills,
e. food and beverage plants,
f. metallurgical plants,
g. mines,
h. steel mills,
i. construction industry,
j. dredging,
k. sewage treatment,
l. water treatment.

The ever-widening scope of slurry pipeline transport was not accompanied initially with definite improvements in the technology, except for improved centrifugal pump design to allow larger solids to be pumped in greater quantities over longer distances without unacceptable pump wear rates. Before 1950, hydraulic transport systems were designed on the basis of previous experience and the use of published data correlations. These correlations could not be applied beyond the range of practical experience with any confidence. Nevertheless, hydraulic transport became firmly established in the chemical, mining and civil engineering industries because of the advantages it offered in regards to cost and convenience, and in many cases due to the impracticability of using any other method.

In the 1950's, a beginning was made to correlating the flow parameters of solid-liquid mixtures in the form of fairly stable suspensions for the design and optimization of hydraulic transport systems. This process of developing correlations for prediction of the flow conditions of various slurries has continued up to the present day and designers now have methods for both stable and coarse suspensions.

As requirements became more demanding, positive displacement pumps began to complement the centrifugal pump and now deliver the high pressure flows required by long distance slurry pipelines. Improvements in pipe materials, methods of pipeline construction, and pumps, now permit pipelines of 1,000 km or more operating at high pressures to deliver as much as 25 million tonnes per year of solid material.

2.9 REFERENCES

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3. CONVENTIONAL LIQUIDS PIPELINE DESIGN

by

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3.1 INTRODUCTION

Transport of a liquid in a pipeline is relatively simple compared to the transport of most slurries. The fluid mechanics of a liquid such as water has been investigated thoroughly, both experimentally and theoretically, over a long period of time. On the other hand, the complexity of the flow of slurries in a pipeline has hampered the development of theoretical explanations of slurry flow. Mathematical equations for design purposes have become available in the last 30 years, but even today there are no reliable equations which cover all slurry flow regimes. Consequently, the approach taken in this manual, in regard to the basic design of a slurry pipeline, is to illustrate first the design of a conventional liquid pipeline, such as a crude oil pipeline. In Chapter 7 the reader is introduced to the more complicated fluid mechanics of slurries. Then, in Chapter 8, the design of slurry pipelines is described in detail.

Design of a pipeline system, regardless of commodities to be transported, generally follows a common procedure which requires the performance of a number of activities:

a. route selection,
b. hydraulic design,
c. mechanical design,
d. design of pumping facilities.

Route selection usually begins with drawing a line on a map as a preliminary route which then would be improved as information becomes available. The preliminary route provides the designer with an approximate location and a reasonable estimate of the length of the line.

Using this length and a flow velocity suitable for the commodity to be transported as a basis for the preliminary hydraulic design, a line size and estimate of pumping power requirements can be calculated. With the additional input of a figure for the maximum operating pressure (MOP), the wall thickness of the pipe and hence the quantity or weight of steel required can be calculated. The next step could be optimization of the preliminary design parameters by performing a series of tariff or cost of service computations for different throughput conditions and line sizes and comparing the required revenues for the selected alternatives.

In the following sections, a detailed description is given of the design activities and how they interact and affect the system design and operating economics.

3.2 ROUTE SELECTION

The axiom "the shortest distance between two points is a straight line" holds true for selecting pipeline routes, and the ideal pipeline route would run in a straight line.

Unless there are major obstacles in the way which are either impossible or impractical to traverse or which would take a disproportionate amount of effort to overcome, the shortest pipeline route results in the lowest installed cost.

For example, if in a preferred route there is a 2 km section which would be difficult to construct and the alternate route avoiding the area would be 1 km longer, it still would be more economical to take the shorter route if the incremental cost of construction through the difficult 2 km stretch does not exceed the total cost of the extra kilometre.

Using topographical maps, aerial photographs and field reconnaissance as sources of information, the route is developed then by identifying areas to be avoided, suitable sites for crossings with roads, railways and watercourses, and using common sense in avoiding built-up areas, farmsteads, environmentally sensitive spots and other locations where a pipeline would be undesirable.

Large bodies of water, major rivers, unstable slopes or other topographical obstacles require special investigation and design considerations.

An assessment of the environmental impact of a pipeline is mandatory for practically all proposed installations and, as the results of environmental studies may affect the selected route, it is essential that the environmental studies are part of the route selection process.

3.3 HYDRAULIC DESIGN

The hydraulic design of a pipeline system encompasses several activities including the selection of pipe diameter, computation of friction losses and pumping requirements, and the selection of pump station sites.

3.3.1 Selection of Pipe Diameter

Selection of a diameter for a pipeline is as much a result of economic considerations as hydraulic design. The first step is to select a pipe diameter based on a reasonable flow velocity for the commodity to be transported. The next step could be to select one or more larger and smaller pipe diameters, a number of alternate throughput figures and complete a preliminary design and cost estimate for the alternatives considered. Preliminary designs would include calculations of required pumping power, location of pump station(s) and calculation of wall thickness. Plotting the computed average cost of service (refer to Section 3.6) for each line size and throughput condition results in a set of "J" curves indicating which option would perform most economically. As the pipe cost is one of the major, if not the largest, single cost item of a pipeline system, the correct selection is important. As both length and wall thickness can be estimated with good accuracy early in the life of a project, the economic comparison is quite reliable.

3.3.2 Pressure Drop Calculation

Pressure drop in a pipeline is a function of the pipeline's diameter and length, its wall roughness, the flow velocity and the properties of the fluid to be pumped. Over the years, flow formulae have been developed to suit particular types of fluids and operating conditions. Prior to the availability of programmable calculators and computer systems, hydraulic calculations were performed with hydraulic slide rules which were specially designed to match a particular flow formula. Currently there are programs with varying degrees of sophistication available which will generate all hydraulic data needed in a very short time. The accuracy, of course, is still only as good as the input data used.

3.3.2.1 Flow Formulae. Currently the most universally accepted flow formula for incompressible liquids flowing in pipes is based on the D'Arcy Weisbach equation:

$$h_f = \frac{fLV^2}{2gD} \qquad ...3.1$$

where h_f is the friction head loss in terms of metres of fluid.

When converted to substitute velocity with throughput volume, Equation 3.1 becomes:

$$h_f = \frac{82.66 \times 10^{-3}\, Q^2 f}{D^5} \quad \frac{\text{m of fluid head}}{\text{m of pipe length}} \qquad ...3.2$$

Using units commonly used in the pipeline industry, the formula can be written as:

$$\Delta h = \frac{11.07 \times 10^6\, f\, Q^2}{D^5} \text{ m/km} \qquad ...3.3$$

$$\Delta p = \frac{108.6 \times 10^3\, f \rho L\, Q^2}{D^5} \text{ kPa} \qquad ...3.4$$

where: Δh = friction loss in m km,
Δp = pressure drop in kPa,
Q= throughput in m^3 day,
L = length of line in km,
D= internal diameter in mm,
f = D'Arcy friction factor,
ρ = density in kg m^3.

Reversing the formulae and solving for Q:

$$Q = 0.3006 \times 10^{-3} D^{2.5} \left[\frac{\Delta h}{f}\right]^{0.5} \qquad ...3.5$$

$$Q = 3.034 \times 10^{-3} D^{2.5} \left[\frac{\Delta \rho}{Lf\rho}\right]^{0.5} \qquad ...3.6$$

Another formula for products and water pipelines is the Hazen and Williams formula:

$$\Delta h = \frac{3.146 \times 10^9 \quad Q^{1.852}}{D^{4.87} \quad C^{1.852}} \text{ m km} \qquad ...3.7$$

$$Q = 7.434 \times 10^{-6}\, \Delta h^{0.54}\, D^{2.63}\, C \text{ m}^3 \text{ day} \qquad ...3.8$$

where "C" is the Hazen Williams "C" factor which is a function of the fluid viscosity and pipe roughness. The "C" factor is an empirical coefficient applicable to water flowing in relatively smooth pipe at velocities less than 3 m s.

A typical "C" factor for water in a smooth, straight pipe is 150.

3.3.2.2 Reynolds Number. One of the most important parameters in fluid mechanics is the dimensionless Reynolds number which determines the flow regime.

$$Re = \frac{DV\rho}{\mu} = \frac{1.2732\, Q}{D\upsilon} \qquad ...3.9$$

Converted to commonly used pipeline units, Equation 3.9 becomes:

$$Re = \frac{14737\, Q}{D\upsilon} \qquad ...3.10$$

where: Q = throughput in m^3/day,
D = internal pipe diameter in mm,
υ = kinematic viscosity in centistokes (cSt).

3.3.2.3 Flow Regimes. Laminar flow is the condition where fluid particles move along in smooth layers which travel at different velocities. The layer in contact with the pipe wall is not moving, while the layers at the centre of the pipe are moving at the highest velocity. Laminar flow

occurs when the Reynolds number is smaller than 2000.

In a turbulent flow situation, i.e., Reynolds number greater than 4000, the fluid particles move in irregular paths causing higher shear stresses and hence higher friction losses. Most pipelines do not operate in the fully turbulent range but are in the transition zone between smooth pipe flow and rough pipe flow (Ref. 1).

The region between laminar and turbulent flow is generally referred to as the critical zone.

3.3.2.4 Friction Factor. The friction factor referred to in this chapter is the D'Arcy Weisbach friction factor. In the laminar flow regime the friction factor is a function of the Reynolds number only.

$$f = 64 / Re \qquad ...3.11$$

Many researchers have attempted to experimentally arrive at a formula which expresses the friction factor as a function of the Reynolds number and pipe roughness. The result of this work is the generally accepted Colebrook-White correlation and the Moody Diagram.

The Moody diagram (Ref. 2) is a graphic correlation showing friction factors for laminar flow and flow in the transition and turbulent zones as a function of Re and relative roughness. The Colebrook-White correlation is a mathematical equation which yields the same friction factors for the transition and turbulent zone flow regimes. It has some disadvantage in that the term f appears on both sides of the equation which requires iteration to solve.

$$[1/f]^{0.5} = -2 \log \left[\frac{k}{3.7D} + \frac{2.51}{Re\,(f)^{0.5}} \right] \qquad ...3.12$$

Alternately, the term "flow coefficient" expressed as F has been used. For $F = (1/f)^{0.5}$, Equation 3.12 becomes

$$F = -2 \log \left[\frac{k}{3.7D} + \frac{2.51F}{Re} \right] \qquad ...3.13$$

where: k = pipe roughness,
D = pipe diameter.

Recently Churchill and Usagi (Ref. 3) have proposed a single equation to compute the friction factor.

$$f = 8[(8/Re)^{12} + 1/(A + B)^{1.5}]^{0.0833} \qquad ...3.14$$

where: $A = [2.457 \ln (1/[(7/Re)^{0.9} + 0.27k/D])]^{16}$,
$B = [37530/Re]^{16}$.

The above formula is valid for any Re from laminar to turbulent flow.

3.3.2.5 Pipe Roughness. The Colebrook-White friction factor correlation requires either the internal diameter and absolute roughness of the pipe, or its relative roughness.

The figure commonly used for absolute roughness for steel pipe is 0.046 mm or, as given in its original form, 0.00015 ft. For new clean steel pipes, absolute roughness figures of 0.013 to 0.025 mm could be used (Ref. 4). The sensitivity of the friction factor to changes in pipe roughness is very low which is not a great incentive for much refinement in the roughness figures.

Example: For a reduction in absolute roughness from 0.046 mm to 0.013 mm, the friction factor would be reduced between 1% and 2% for pipes ranging from 0.2 m to 1.6 m with a flow velocity of 1.5 to 2 m/sec.

3.3.3 Properties of Fluids

Fluids transported by pipeline may vary considerably from one system to another and even in the same system for pipelines which transport batches of different materials. The materials may range from heavy oils, which have to be heated to be pumpable, to refined products and natural gas liquids with viscosities as low as 0.5 cSt. As all fluid properties are affected by changes in temperature and pressure, fluid properties should be considered in the operating pressure and temperature ranges. In the succeeding sections, the following properties are examined: density, compressibility, viscosity, vapour pressure and pour point.

3.3.3.1 Density. Density is given in kg/m^3 in the SI System which is used in this manual. In the North American petroleum industry, the density or "gravity" of a liquid is commonly indicated in degrees API (° API). In other areas of the world, specific gravity (SG), also referred to as relative density, has been adopted as the system to express the density. Currently all three systems are in use and care should be taken that the correct units are used in formulae.

To convert SG to density in kg/m^3, one multiplies by 1000.

The conversion from ° API to SI units and vice versa is as follows:

$$\rho = \frac{141.5 \times 10^3}{131.5 + G} \qquad ...3.15$$

$$G = \frac{141.5 \times 10^3}{\rho} - 131.5 \qquad ...3.16$$

where: G = density in degrees API,
ρ = density in kg/m^3.

The density is generally given at a reference temperature of 15° C (formerly 60° F) which is used as the base or reference temperature for measurement in the petroleum industry.

The density varies with temperature at a rate which is a function of the density as well as the change in

temperature and the type of material. Refer to Reference 5 for tables and formulae.

3.3.3.2 Compressibility. The compressibility of a fluid varies with density and pressure. When a fluid is compressed, it becomes more difficult to compress as the pressure increases. The compressibility of a fluid is expressed by its bulk modulus (K); the lower the number for K the more compressible the fluid is.

If the pressure on a unit volume is increased by an amount dp, its volume will change by dV. The ratio dp dV determines the bulk modulus K.

For a given volume V of a liquid the decrease becomes Vdp dV, or

$$K = \frac{dp}{dV\ V} \qquad ...3.17$$

where K is expressed in the same units as the pressure.

Typical values of K at atmospheric pressure are:

water	2070 MPa	(300 000 psi)
crude oil	1275-1860 MPa	(185 000-270 000 psi)
gasoline	1070 MPa	(155 000 psi)

For steady state hydraulics in liquid pipelines, most fluids may be considered incompressible. When computing line fill under pressure for measurement or throughput balance systems, the fluid compressibility may become significant.

3.3.3.3 Viscosity. Fluids may be classified as Newtonian or non-Newtonian (Ref. 6). For Newtonian fluids, there is a linear relationship between applied shear stress and resulting rate of deformation. For non-Newtonian fluids, this relationship is non-linear. The slope of this relationship is the viscosity which is a measure of the resistance to shear.

In this chapter, only Newtonian fluids are considered, as most liquid hydrocarbons are Newtonian or may be considered Newtonian under the operating conditions considered.

Viscosity is a function of temperature, pressure, and molecular species. For non-Newtonian fluids, the viscosity is also a function of the local velocity gradient.

The dynamic viscosity is expressed in Pa•s (pascal seconds). The kinematic viscosity is expressed in m^2/sec. The relationship is

$$\upsilon = \mu / \rho$$

Common units used in the pipeline industry for viscosity are:

a. dynamic viscosity in centipoises
   1 poise = 100 centipoises(cp) = 0.1 Pa•s
b. kinematic viscosity in centistokes,
   1 stoke = 100 centistokes(cSt) = 10^{-4} m^2/sec

Other units used to express fluid viscosities are Saybolt Universal Seconds (SUS) and Saybolt Furol Seconds (SFS).

Conversion methods between units of viscosity are given in Reference 7.

Converting Saybolt Universal Seconds to centistokes can be done by the following formulae:

for t over 200 sec

$$\upsilon(cSt) = 0.216\ t \qquad ...3.18$$

and for t between 32 to 200 sec.

$$\upsilon(cSt) = 0.221\ t - \frac{183}{t} \qquad ...3.19$$

where: υ(cSt) = viscosity in centistokes,
t = viscosity in Saybolt Universal Seconds.

Equation 3.18 is accurate to ±0.5% and Equation 3.19 is accurate to ±1.5%, except at viscosities below 40 SUS where the accuracy deteriorates rapidly.

The above conversion formulae are given for conversion of viscosities at 100° F (37.8° C).

Reference 7 gives correction methods for conversion at other temperatures. However, as the correction is in the order of 0.01% per °C of difference, there will be little need for this refinement.

3.3.3.4 Effect of Temperature on Viscosity. Changes in fluid temperature greatly affect its viscosity which should be taken into account when performing friction loss calculations. The change of viscosity with temperature is a function of the viscosity, the density and composition of the fluids under consideration. The American Petroleum Institute (API) and the American Society for Testing of Materials (ASTM) (Ref. 7) have published viscosity-temperature charts for different ranges of viscosity and temperature. These charts have the common feature that, for Newtonian fluids, all viscosity points fall on a straight line when plotted in this manner. Thus, if for a certain product, viscosities are given at two different temperatures, the viscosity at the desired temperature can be read by drawing a straight line through the two known points.

As computers and programmable calculators do not read charts, another method of inputting viscosity temperature data is desirable. One method is by inputting a viscosity/temperature table and having the program interpolate between the nearest two known values. If the temperature intervals do not exceed 10°, this method is generally acceptable. Another method is by the following correlation which mathematically duplicates the API/ASTM chart method. The correlation will yield the viscosity at selected temperature T, when two viscosities and temperatures are given.

Basic equation: $y = a - bx$ ...3.20

where: $y = \log [\log (\upsilon + 0.75)]$ = viscosity scale,
$x = \log T$ = temperature scale,
T = absolute temperature (°C + 273.15),
a and b are constants determined by the property of fluid under consideration,
υ is in centistokes.

By substitution Equation 3.20 becomes:

$$\log [\log (\upsilon + 0.75)] = a - b \log T \qquad ...3.21$$

where: $b = \dfrac{y_2 - y_1}{x_1 - x_2}$ and $a = y_1 + bx_1$

x_1 and y_1 are x and y (Equation 3.20) respectively at reference temperature T_1 and viscosity υ_1.

x_2 and y_2 are as above for temperature T_2 and viscosity υ_2.

Procedure: Compute x_1, x_2, y_1, y_2, a and b. Substitute a and b in Equation 3.21. Solve for given temperature T.

Accuracy of computed viscosity is in the order of ±5% for range of -20° C to 140° C when T falls between T_1 and T_2 and $T_1 \pm 10°$ and $T_2 \pm 10°$ C.

3.3.3.5 Viscosity of Liquids Under Pressure. Reference 7 gives a formula for computing the viscosity of liquids under pressure.

$$\log \frac{\mu}{\mu_o} = \frac{p}{6800} [0.0239 + 0.11177\ \mu_o^{0.278}] \qquad ...3.22$$

where: μ = viscosity in Pa•s at temperature T and pressure P,
μ_o = viscosity at temperature T and atmospheric pressure,
p = pressure in kPa.

At pressures of 35,000 kPa and lower, the approximate error is 5%. For pipeline operating pressures in the 1000 to 10,000 kPa range, expected accuracy should be better.

3.3.3.6 Vapor Pressure and Pour Point. The vapor pressure of a fluid is a measure of its volatility. "Reid Vapor Pressure" (RVP) is a description given by ASTM of the vapor pressure of a liquid determined under a set of reproducible conditions at a temperature of 37.8° C ± 0.1° (100° ± 0.2°).

Vapor pressure is generally not of importance for friction loss calculations but, for materials with high RVP's, the hydraulic design has to ensure that the fluid is maintained under sufficient pressure at all times. Vapor pressure is also an important parameter for the determination of the available net positive suction head (NPSH) when selecting pumps.

Pour point is generally referred to as the temperature at which oils change from the liquid phase to an apparent solid state and thus are no longer pumpable.

3.3.4 Pumping Requirements

3.3.4.1 Static Head. Friction loss calculations will determine the pressure required to pump the liquids through a pipeline. If the end of the pipeline is at a different elevation than the beginning of the pipeline, the pumping effort will either be aided or opposed by the difference in elevation, referred to as static head.

The static head equals a column of liquid with a height of the elevation difference. When computing pumping pressures the "conventional way", care should be taken that the correct density (i.e., at operating pressure and temperature) is used to compute static head for significant elevation differences.

Computer programs generally calculate pressure drop and static head for small incremental sections of the pipeline using the correct density at flowing temperature and pressure. Of course, static head computations are only as accurate as the pipeline profile data available.

3.3.4.2 System Curve. Plotting the total pumping pressure required against Q, a system curve is obtained for the line under consideration. Figure 3.1 gives the system curve for a 457 mm OD pipeline of 150 km in length pumping crude oil with a density of 850 kg m^{-3} and viscosity of 10 cSt. Overlaid on the system curve are pump curves for a number of identical pumps. The maximum throughput for each pump combination is read at the

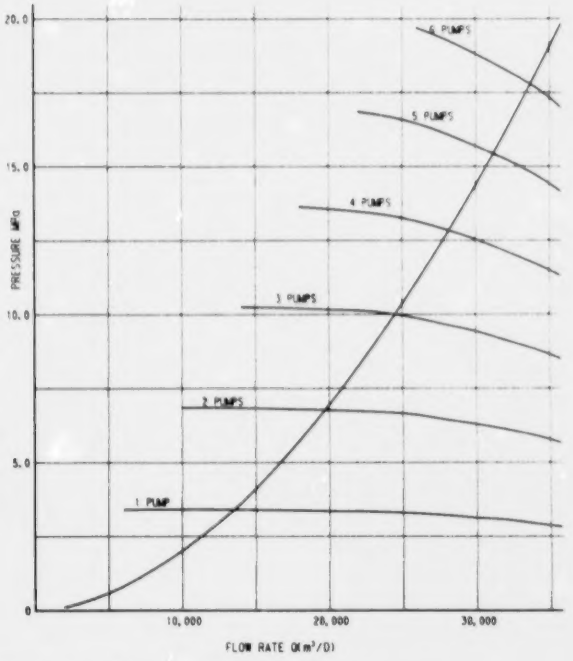

Figure 3.1 Pipeline system curve & pump curves

intersection of the pipeline curve with the pump curve. It should be noted that the pressure found at the intersection of pump curve and pipeline curve is the total pumping pressure which, as depicted in Figure 3.1, exceeds the MOP when more than three pumps are used. In such a case, pumps would be installed in two or more pump stations. The method of selecting pumps is covered in more detail in Section 3.5.

With the virtually unlimited capabilities of modern computers, it is now practical to input a number of selected pump curves into a system and program it to select the correct pump combinations.

Whereas there is no doubt that the computer method is much faster, the graphic method has the advantage to the designer in that it provides a better overview of what is happening in the system.

3.3.4.3 Hydraulic Gradient. Figure 3.2 gives the hydraulic gradient and profile for the pipeline described above. It has been assumed that a residual terminal pressure of 500 kPa is required to move the oil through terminal piping into tanks. The figure shows that operation with one pump only would produce a gradient which intersects with the hill at km 100. If the line has to be operated at such a low throughput, sufficient back-pressure has to be maintained at the terminal to ensure positive pressure at the high point to ensure that no cavitation occurs. The booster station is located at a higher elevation than the origin and terminal, and this fact causes the booster station site to be moved closer to the main pump station and restricts throughput under some pumping conditions. The hydraulic gradient and pipeline profile were used by designers to locate intermediate booster stations and find problem areas such as indicated in Figure 3.2 for the single pump alternative where the gradient intersects with the profile. The availability of computer techniques has eliminated the need for a hydraulic gradient, as pressure drops are computed on a regimental basis and the computer would print for each line segment the inlet or outlet pressure, elevation, temperature and pipe wall thickness and grade required. As the composite drawing of hydraulic gradient and pipeline profile has a much better visual impact than a table with columns of numbers, it still is a useful item for the designer. Graphics programs evolving in every increasing abundance have the capability to provide hydraulic gradients for whichever operating conditions are required, almost instantaneously.

3.3.5 Transient Flow Design

Although a long distance pipeline could be considered the ideal example of steady state operations, changes do occur; pumps are stopped from time-to-time and occasionally an emergency arises requiring quick action. For long lines with large numbers of pump stations, it would be desirable to know what will happen when an abrupt change occurs.

The most risky condition is a sudden valve closure which creates a surge wave, similar to a water hammer. The surge wave travels upstream until it reaches a reflection point, such as the next upstream pump station, and returns down the line. If there were no damping or friction, the system would oscillate indefinitely.

Formulae for computation of the magnitude of the surge and its speed of travel, as given in Reference 1, are:

$$\Delta p = \frac{\rho \Delta V\, a}{102g} \qquad ...3.23$$

where: Δp = pressure change at point of instantaneous stoppage in kPa,
ρ = density of liquid kg/m^3,
ΔV = change in liquid velocity m/sec,
a = velocity of pressure wave front in m/sec.

$$a = 10.1\ [\rho\, g\,(1/K + D/bE)]^{0.5} \qquad ...3.24$$

where: K = bulk modulus of fluid in kPa,
E = modulus of elasticity of pipe,
D = external pipe diameter in mm,
b = pipewall thickness in mm.

The damping and friction effect on the surge wave are functions of the compressibility and viscosity of the fluid and are difficult to define (Ref. 8). With modern computer techniques, it has become possible now to simulate complete systems mathematically, including the pump and control valve characteristics. This enables a long distance pipeline company to play "what if" games, to verify designs for new or modified facilities, and have an operator training facility which duplicates the real system so closely that even trained operators cannot distinguish between the "real" and "soft" pipeline.

3.4 MECHANICAL DESIGN

Mechanical design for pipelines is generally minimal. A buried line is considered fully restrained and the only mechanical strength required is that needed to withstand the hoop stress created by the internal pressure. The formula for wall thickness design is (Ref. 9):

$$t = \frac{p\, D\, 10^{-3}}{2\, S\, F\, E} \qquad ...3.25$$

where: t = wall thickness in mm,
p = design pressure in kPa,
D = outside diameter of pipe in mm,
S = specified minimum yield strength of pipe material in MPa,
F = design factor (.72 or smaller),
E = longitudinal joint factor (1.0 for most types of pipe).

Areas where mechanical strength becomes of concern are where the line connects to above ground facilities, is

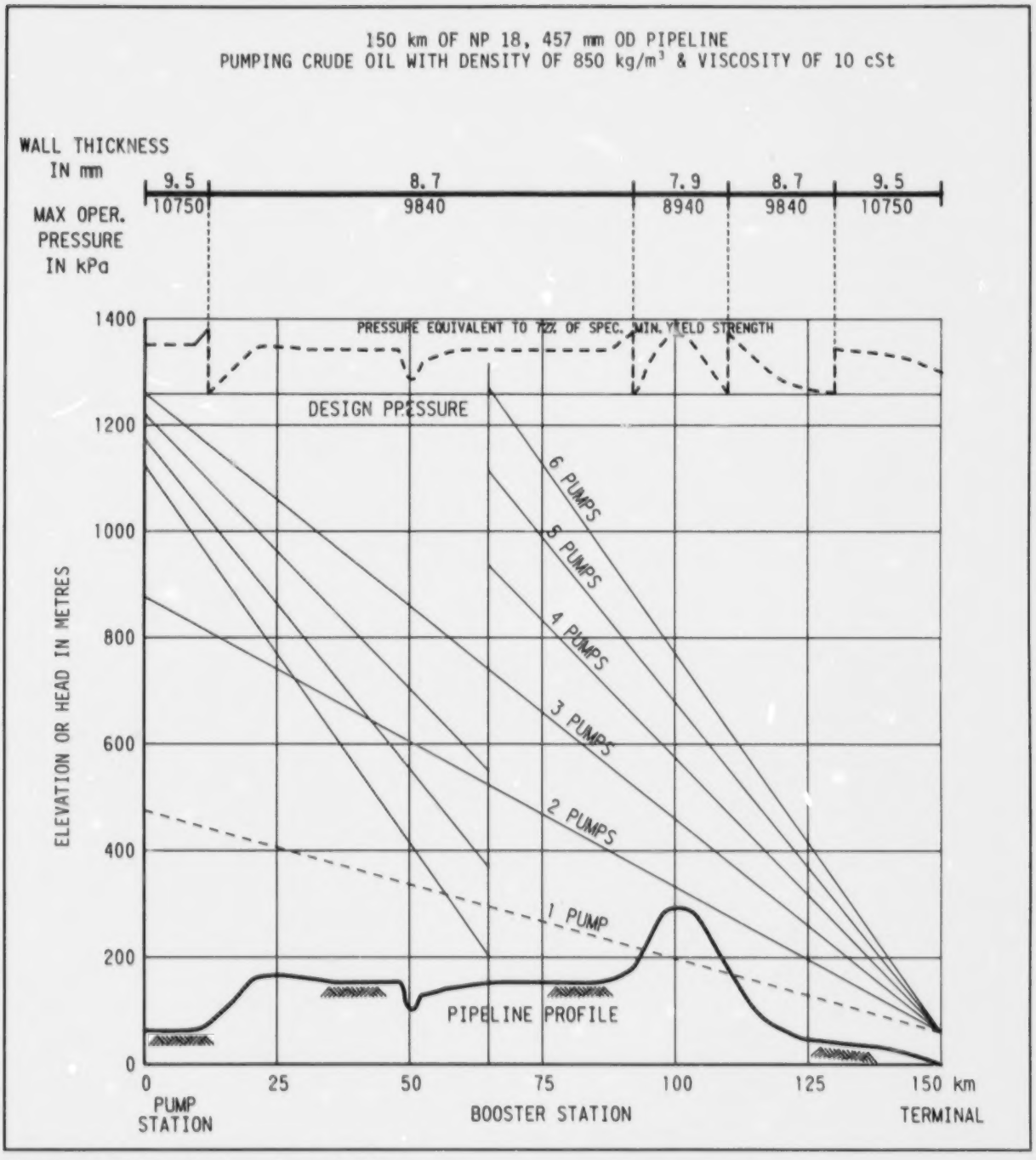

Figure 3.2 Profile, hydraulic gradient and MOP

partially installed above ground, is subject to movement due to unstable ground or seismic activity, and at sharp bends. Cases identified as potential high stress areas should be analyzed to ensure that potential combined stresses during operations do not exceed limits. Several stress analysis programs are available for this purpose from computer user service bureaus.

Materials used for pipelines, such as pipe, valves, fittings and flanges should be specified to suit the service requirements. Special care should be taken where liquids contain H_2S or brine, or where extreme temperatures may occur.

Canadian standard specifications for line pipe are given in the Z245 series of standards of the Canadian

Standards Association (CSA). Other pipe specifications are available from API and ASTM.

It should be noted that these standards give minimum requirements and general specifications, and that supplemental requirements may have to be specified to suit specific conditions.

3.5 PUMPING FACILITIES

The selection of pump station sites depends on topography, operating conditions and maximum operating pressure selected. The selection of type of pump depends on conditions of service, fluids to be pumped and availability.

3.5.1 Types of Pumps

The centrifugal single or two-stage pump is most commonly in use for long distance and high volume pipelines. It provides reliable service at an efficiency between 80% and 86%, depending on make, size and service.

Other types of pumps used in pipeline service are positive displacement pumps, either rotary or reciprocating. Rotating positive displacement pumps are in use on pipelines moving heavy oil blends such as the Manito system in Saskatchewan where the high viscosity of the oils makes efficient use of centrifugal pumps impossible.

Reciprocating pumps, which generally are multi-cylinder single or double acting pumps, are most commonly used in gathering systems where a nearly constant output rate into a system with wide variations in line pressures is desired.

3.5.2 Selection and Operation

Where multiple centrifugal pumps are used, the common operating mode is in series, where the whole stream passes through each pump which increases the pressure. Pumps may all be located in one pump station for shorter lines or in two or more stations in order to keep the maximum operating pressure lower. The example in Figure 3.2 uses two pump stations. Operational combinations can be varied for multiple pump combinations such as 3+0 or 2+1, 3+1 or 2+2 and 3+2 or 2+3. Not all combinations may be achievable in the example due to the geographic constraints. Pumps are selected such that they match pressure and volume requirements and operate at or near maximum efficiency at the maximum throughput conditions. An installation with three pumps per station, sometimes with a spare fourth unit as standby, is a practical combination. The pumps can be all identical or be two full head units and one half head unit to provide more flexibility in operations. In the example given in Figure 3.1, all pumps are of the same size and it can be seen that when going from two pumps on line to three pumps on line the throughput would increase from approximately 20,000 m^3/day to 24,500 m^3/day. By using a half unit, this increment could be reduced.

In cases where the static head is large compared to the frictional pressure drop in the line, such as in a line crossing a mountain range, it may be more practical to operate pumps in parallel. Each pump would provide sufficient discharge pressure to overcome the full static head plus friction losses and would provide part of the stream flow. In such cases, high head multi-stage centrifugal pumps would be used.

The most common driver for pumps is the single speed induction motor. The motors are simple in design, in most cases are started directly on line and require a minimum of control equipment.

Where electric power is unavailable, pumps are driven by engines or turbines which do have the advantage that their speed can be controlled. Single speed electric drive stations generally rely on a control valve to provide the pressure control required to keep the line in balance and control flowrates. A similar effect can be obtained by equipping one or more pumps in each station with a variable speed drive system. Comparing both systems, it is found that during the ideal operational condition, e.g., no throttling or speed reduction, the control valve would be fully open and its losses lowest. Under the same condition with a variable speed drive system the motor load would be maximum and hence the extra losses introduced by the drive system would be at their maximum. Variable speed drives used in oil pumping stations traditionally have been magnetic (eddy current) or hydraulic types. More recently, electronic frequency control systems have become available for use with large induction motors.

Unless there are operational considerations such as a system batching liquids with great differences in density for which variable speed pumps are ideal, a designer contemplating the use of variable speed electrically driven pumps is well advised to compare the installed and operational costs carefully for the available options.

For use with positive displacement pumps where flow control has not been practical, the use of variable speed drive will greatly enhance the operational flexibility.

3.5.3 Location of Station Sites

The location of intermediate booster stations depends on the hydraulics of the pipeline and the topography. In the example used in Figure 3.2, it can be seen that the booster site is not located at exactly the midpoint of the pipeline. The higher ground elevation near the middle of the line dictates that the booster station be moved towards the origin to ensure that sufficient suction pressure is available at the booster station. The location was selected to give the best match for the six pump configuration. For a combination of four pumps, two per station (as indicated in the calculations in Appendix 3-1), there would not be enough suction pressure at the booster station and the system would have to be throttled back to provide the suction pressure, thus reducing the throughput. The hill shown at km 100 has no influence on the booster station location, as it is downstream.

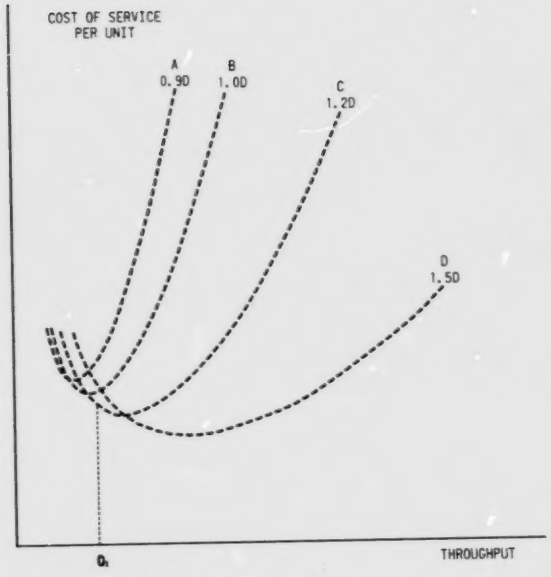

Figure 3.3 Typical "J" curves

3.6 ECONOMIC CONSIDERATIONS

Pipelines, like other carriers, generally provide a service for a fee or tariff, expressed in $\$/m^3$ or similar units.

The tariff or cost of service represents the cost of operations, cost of capital, depreciation, taxes and profit, or rate of return on investment.

A pipeline is a very capital intensive operation and usually the largest part of the cost of service is represented by the cost of capital. The next largest cost is generally the power or fuel cost for the drivers.

Evaluation of alternatives involves estimating cost of service for three or more line sizes at different throughputs and plotting the resulting average tariffs for the estimated life of the project on a set of curves which are commonly referred to as "J" curves because of their shapes (Refer to Figure 3.3). The alternative, giving the lowest cost of service at the desired throughput, is the optimum for the chosen conditions.

Financial conditions selected for the economic evaluation are important, as different assumptions for debt/equity ratio and interest rates have a significant influence on the tariff.

The curves in Figure 3.3 represent the average cost of service at different throughputs for a number of alternate line sizes with diameters 0.9D, 1.0D, 1.2D and 1.5D. For a given throughput Q, it can be seen that alternative B is near its optimum performance but alternative C with a slightly larger diameter would have a lower cost of service. In cases where two alternatives would have almost identical costs of service figures, other considerations such as future throughputs and initial capital investment would be used to make the final selection.

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APPENDIX 3-1 EXAMPLE

Pipeline 150 km long, outside diameter 457 mm (18"), MOP 9930 kPa, required terminal pressure 500 kPa, profile as given in Figure 3.2.

What is the maximum throughput, wall thickness and incremental throughput figures when using two pump stations with three equal pumps, each when pumping crude oil with density of 850 kg/m^3 and a viscosity of 10 centistokes at average operating conditions?

Wall thickness based on CSA grade 359 pipe.

$$t = \frac{p\,D\,10^{-3}}{2\,S\,F\,E}$$

where: p = 9930 kPa,
D = 457 mm,
S = 359 MPa,
F = 0.72,
E = 1.0.

t = 8.8 mm, next largest standard wall thickness 9.5 mm.

Compute p for incremental flowrates using Equation 3.4 and plot total pressure for whole length of the line at different throughputs (given in Figure 3.1).

Throughput without booster station, max. 24,600 m^3/day @ 9930 kPa pressure. Note the residual pressure at the terminal balances out the positive static head of 500 kPa.

Select pumps (from manufacturers' catalogs) with suitable curves to match requirements, plotted in Figure 3.1, and read off maximum throughputs.

No. of Pumps	Total p kPa	Q m^3/day	Δp/km kPa/km
1	3400	13,500	22.67
2	6750	19,900	45.00
3	9900	24,600	66.00
4	12750	28,300	85.00
5	15350	31,300	102.33
6	17650	33,700	117.67

The hydraulic gradients for the pump combinations listed above are plotted in Figure 3.2. The gradients are in m of head from common reference elevation of 0.0 m at the terminal.

Sample Calculations

Case of 6 pumps (3 + 3).

- Δp = 117.67 kPa/km
- Discharge head @ pump station, 8825 kPa or 1059 + 60 m = 1119 m
- Static head and suction head at booster station = 200 m
- Total friction head available = 919 m
- 919 m x 8.333 = 7658 kPa/117.67 kPa/km = 65.08 km
- Booster location at 65.08 km max. from origin.
- Discharge at booster 8825 kPa + 200 m = 1259 m or 10492 kPa
- Residual pressure at terminal 10492 - (85 x 117.67) = 490 kPa

Case of 4 pumps (2 x 2).

- Δp = 85 kPa/km
- Discharge at pump station 6375 kPa + 500 kPa static = 6875 kPa
- 6875 - (65 x 85) = 1350 kPa residual static plus suction head at booster station. 1350 kPa = 162 m @ elev. 150 m leaves only 12 m or 100 kPa suction pressure which is not enough.
- Booster should have been located closer to main pump station.

Other design features indicated in Figure 3.2 are the reductions in all thickness made possible by the higher ground elevations in the central part of the system.

The line shown for design pressure, being the MOP at the pump station discharge, will not be exceeded even under completely shut-in conditions. Adding the full design pressure to the static head at the higher elevations would result in an over-designed line. The graph shown represents the equivalent pressure at 72% of specified minimum yield stress (SMY) of the pipe for the wall thickness listed at the bottom of Figure 3.2.

Notes:

(1) The design is "streamlined". The pressure drop calculations are based on a constant internal diameter disregarding the changes in wall thickness.

(2) Viscosity corrections for different flow conditions and operating pressures were omitted as the influence is relatively small.

(3) No actual length of pipe in the ground was calculated. All calculations are based on horizontal distance only.

4. THE SLURRY PIPELINE SYSTEM

by

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4.1 GENERAL CONSIDERATIONS

To the casual observer, there appears to be no obvious difference between liquid pipelines and slurry pipelines. One sees a metal pipe which gives no visible indication of the rapid transport of liquid or slurry inside. Only at the ends of the pipeline does one see the more complex equipment required by slurry pipelines.

Slurry pipelines can be classified somewhat arbitrarily as in-plant lines, short distance pipelines, and long distance pipelines. In-plant lines are very short lines moving material from one processing stage to another, either horizontally along the plant floor, or vertically between floors, or from the bottom of one piece of equipment to the top of another, such as a tank. Usually, these lines operate under fluctuating conditions and have fairly wide operating capacities. Short distance pipelines can be considered as pipelines carrying materials to or from processing plants and limited to the distance over which a single pump (usually centrifugal) can convey the slurry. Long distance pipelines can be considered as lines moving material over distances of 10 km or more and probably using more than one pump station. From the fluid mechanics point of view of design, there is little difference between short and long distance pipelines.

A long distance slurry pipeline system consists of a number of elements each of which is an important part of the total system, as shown in Figure 4-1. The solids to be transported have to be prepared in an appropriate form suitable for passing through the pipeline, e.g., ground to a certain particle size distribution and mixed with water (Chapter 5). Then the correct type of pump (Chapter 6) forces the solid-liquid mixture through the pipeline (Chapter 7) at an optimum velocity (Chapter 8). If the pipeline is long, a series of booster pumps spaced along the pipeline relays the slurry from pump station to pump station. Finally, at the terminal, the slurry is separated into its original components, usually by some form of filtration or centrifuging (Chapter 9). The liquid is treated for disposal or recycle while the solids are stored or moved immediately by other methods of transportation to the ultimate consumer. Some variations might be several delivery points or terminals, use of the slurry as delivered, or further transport of the slurry by other means, i.e., a slurry ship.

The designer of a long distance slurry pipeline must consider the economics of the total system, from the point of origin of the solid material to the final utilization, when establishing the specifications for the pipeline part of the system. To illustrate this point, consider the use of pipelines to transport thermal coal to a power plant and metallurgical coal to a preparation plant. In the case of the thermal coal, a relatively long line is involved and the end use requires the coal to be finely ground, i.e., all -200 mesh. Therefore, it is possible to grind the coal before pipelining to a size distribution which minimizes the hydraulic gradient in the pipeline. However, the coal being fed to the boilers in the power plant should have as little water as possible remaining in it in order to maintain boiler thermal efficiency. But the finer the coal is, the more difficult and hence more expensive it is to remove the water. So the system designer has to compare the pipeline savings, from finer grinds, to the added cost of separating the coal from the water at the end of the pipeline, and minimize the total costs within the constraint of optimizing the total system with respect to the final use of the solids. In the case of the metallurgical coal, the end use requires the coal to be fairly coarse. However, the

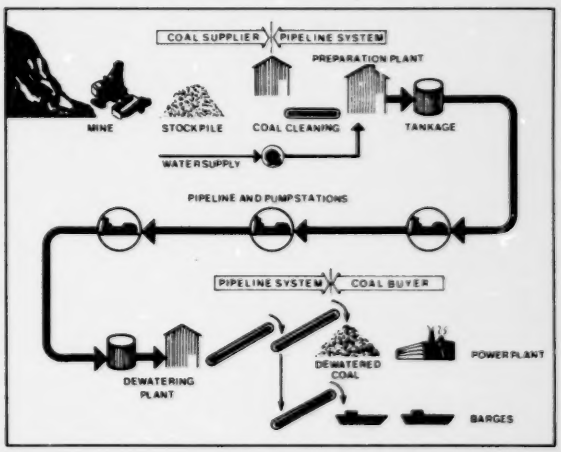

Figure 4.1 Schematic diagram of a long distance pipeline system (by permission, from E.J. Wasp, J.P. Kenney and R.L. Gandhi, Trans Tech. Publications, Clausthal, 1977)

coarser the coal the higher the pumping costs are, and the longer the line the more the coal is attrited. Therefore the designer has to consider the relationships of coal size, pumping costs and pipeline length to unit delivered costs of the coal.

For in-plant slurry pipelines the capital costs of each system are small compared to the total plant costs. The emphasis is on simplifying the transfer of the solids from unit process to unit process and on complete integration of the system into the overall plant process. Hence the processing constraints upstream and downstream of the pipeline are paramount and the transfer system is designed to meet these constraints without emphasis on optimizing the performance of the transfer system itself. For example, if a vacuum crystallizer in a chemical plant is designed to produce a slurry with large crystals to satisfy the requirements of the fertilizer trade, the pump and pipeline to transfer the slurry to filters, centrifuges or dryers for further treatment, are designed to move that specific slurry with as little change to the slurry as possible and little or no consideration is given to modifying the crystal particle size distribution to minimize the cost of the pump and pipeline.

4.2 PIPELINE FLOW REGIME

The flow of single phase fluids in pipelines is homogeneous at all flowrates. On the other hand, the flow of a mixture of solids and liquids in horizontal pipes can be homogeneous, pseudohomogeneous or heterogeneous. Figure 4-2 illustrates three limiting cases which can be analyzed theoretically and are discussed further in Chapter 7. In homogeneous flow, the solids are distributed uniformly over the pipe cross section. Examples of such slurries are thick drilling muds or slurries of non-settling, fine clays. In pseudohomogeneous flow the solids are not distributed uniformly over the pipe cross section, but the flow still behaves as if the solids were uniformly distributed. The third limiting case involves segregated flow, where the solids settle to the bottom of the pipe and move along it as a sliding bed. Slurries of sand and gravel mixtures or coarse tailings can display this type of flow. Of course, there can be any number of flow conditions in between these limiting cases. Also, one type of flow may be changed to another type by changing one or more of the parameters governing the flow. For example, if the flowrate or concentration is increased, or the particle size is reduced, segregated flows can be changed to near pseudohomogeneous flows. Conversely, if the flowrate is reduced sufficiently, a homogeneous flow could become a segregated flow, with further flow reduction leading to a stationary bed and possible blockage of the pipeline.

These characteristics of slurry flow regimes require an in-depth understanding of the flow mechanisms involved. A designer has to account adequately for them in establishing such things as:

a. the minimum velocity in the pipeline at which solids just begin to settle out,

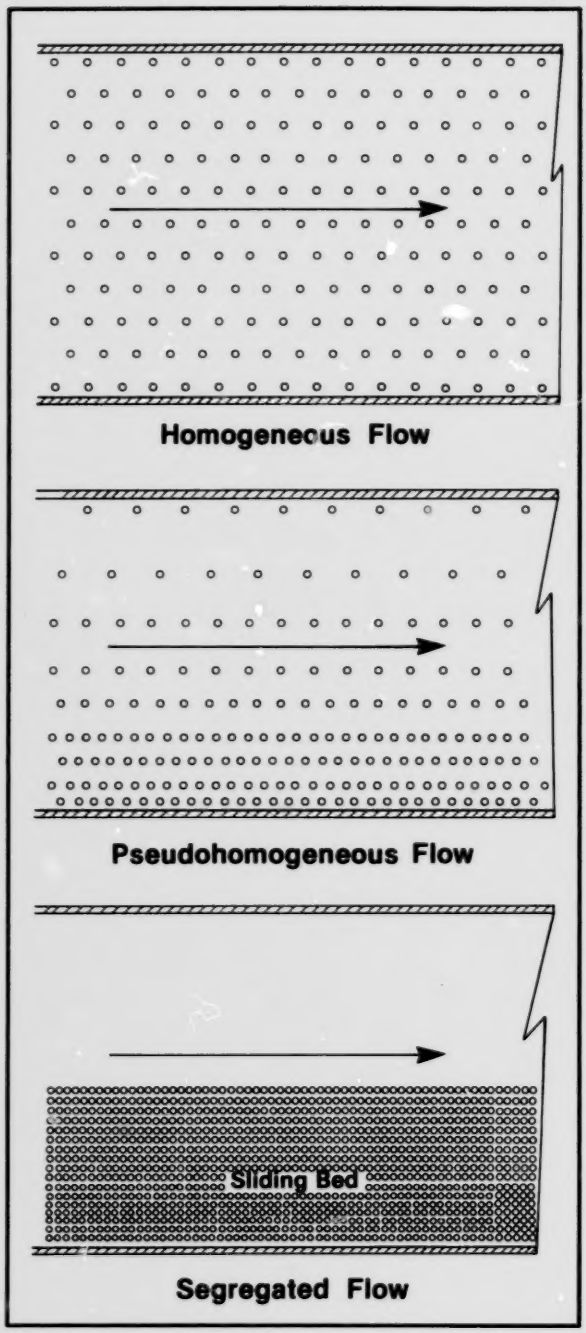

Figure 4-2. Three limiting cases of slurry flow in a pipeline

b. the maximum velocity which can be tolerated as far as erosion of the pipe wall or attrition of the solids,
c. the type of feeder, pump, valves, and instruments to be selected for operating the pipeline,
d. the maximum slope which the pipeline can tolerate,
e. the provisions to take in case of a pipeline shut-down,
f. the method of re-starting a pipeline.

4.3 TYPICAL SLURRY PIPELINE SYSTEMS

A host of in-plant slurry pipelines exist in the chemical processing industry and in base-metal hydrometallurgy. In a typical case the raw materials or ores are prepared in the form of slurries which are transferred in pipes successively from wet grinding circuits to classifying units, to thickners or clarifiers, and to counter-current extractors. The barren or waste solids might then be pumped to disposal sites or tailings ponds. Resulting liquids are sent to crystallizers and the slurry of crystals from the crystallizers may be pumped to thickeners, filters or centrifuges for final separation of the product. More than 50 examples of processes which treat common industrial materials in slurry form, varying from alumina and asbestos to uranium ore and water treatment, are listed in the Chemical Engineers' Handbook (Ref. 1). A new application of considerable importance to the energy crisis is the development of dense coal slurries for feeding boilers in thermal power plants or high pressure reactors for the liquefaction of coal.

Disposal of industrial waste or tailings usually involves short distance slurry pipelines not more than 5 km long. Most metallurgical plants in Canada pump their extracted, residual ores, or tailings as they are called, to tailings ponds for final disposal. More than a dozen pipelines have been transporting uranium bearing gold tailings up to 10 km in South Africa since 1956 (Ref. 2). The Athabasca tar sand plants eventually will have to pump their sand tailings up to 10 km for disposal.

The variety of materials which can be transported in short distance pipelines has been outlined by the Colorado School of Mines (Ref. 3) and by Energy Mines and Resources Canada (Ref. 4). The former indicates 52 short distance pipelines while the latter lists 30.

Hydraulic backfilling or sand filling is a system used to fill underground excavations to limit subsidence and to improve mining operations. Its general acceptance throughout the mining industry reflects the basic simplicity of conveying tailings hydraulically through a pipeline into a mine. The advent of cemented backfill in the late 1950's and the 1960's demonstrated the ability of slurry pipelines to handle chemically reacting slurries under precise requirements of consistency and set-up times (Ref. 5). Canadian companies such as Falconbridge (Ref. 6), Noranda (Ref. 7), and International Nickel use hydraulic back filling extensively.

Hydraulic hoisting of ores from underground mines is used mainly in the gold fields of South Africa and in coal mines. The latter case usually is associated with mines which use hydraulic mining methods. The coal is crushed and ground to sizes required by the particular type of feeder used to inject the coal into the hoisting system. Centrifugal pumps, positive displacement pumps, jet pumps or airlifts are used to pump the slurry to the surface. In 1975 a survey of hydraulic coal mines showed that 18 out of 34 used hydraulic hoisting (Ref. 8). Extensive development work on the method has been done in the Hanza mine in Germany (Ref. 9) and in the Loveridge mine in West Virginia (Ref. 10). Coarse run-of-mine coal up to 60 mm in size has been pumped from a depth of 850 m through a 250 mm pipeline at the Hanza mine. Recently, several international consortia have developed methods of hydraulically hoisting deep sea nodules through pipelines from depths of 4500 m to ore carrier ships on the surface.

The use of dredges to move large quantities of material through pipelines has taken on new applications in Canada. Originally used to deepen waterways and harbours, they have been used in recent years to remove overburden from ore deposits, to create causeways and islands, and to mine saline lakes. The iron ore deposit at Steep Rock in Ontario, and the uranium deposit at Key Lake in Saskatchewan were uncovered by dredges moving millions of cubic metres of rock and soil. Islands in the Beaufort Sea have been created by dredging to establish platforms for oil drilling rigs. A unique dredging operation in Saskatchewan mines sodium sulphate deposits in a saline lake and pumps the crystals and mud through a slurry pipeline to a recovery plant near the lake shore.

Long distance pipelines have increased in size and number since the 1950's. Economically, their advantages increase with distance and tonnage. They are particularly advantageous in remote and rugged terrain. These advantages are reflected in Appendix 4-1 which lists most of the slurry pipelines built in the last 30 years.

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APPENDIX 4-1 Summary of Long Distance Slurry Pipelines

Material	Location	Length km	Diameter mm	Capacity M tonnes/Year	Commencement Operation
Coal	Ohio, U.S.A.	175	250	1.2	1957
Coal	U.S.S.R.	61	300	1.7	1957
Coal	Lorraine, France	10	380	1.4	
Coal	Russia	11		4	1966
Coal	Russia	64	250	1.6	
Coal	Poland	200	250		
Coal	Arizona, U.S.A.	440	460	4.4	1970
Iron concentrates	Savage River, Tasmania	85	230	2	1967
Iron concentrates	Waipipi, New Zealand	10	200 & 300	0.9	1971
Iron concentrates	Pena Colorada, Mexico	45	200	1.6	1974
Iron concentrates	Las Truchas, Mexico	27	250	1.4	1976
Iron concentrates	Sierre Grande, Argentina	32	200	1.9	1976
Iron concentrates	Samarco, Brazil	407	500	10.9	1978
Iron concentrates	North Korea	98		4	
Iron concentrates	Kudremukh, India	66	400 & 460	6.8	1980
Copper concentrates	Bouganville, New Guinea	27	150	0.9	1972
Copper concentrates	West Irian, Indonesia	111	100	0.3	1972
Copper concentrates	Pinto Valley, Arizona, U.S.A.	18	100	0.4	1974
Copper concentrates	Turkey	61	130	0.9	
Copper ore	El Salvador	22	150	0.3	1959
Copper Nickel concentrate	Copper Cliff, Ontario, Canada	12	200	0.7	
Limestone	Columbia	14	130	0.3	1947
Limestone	Trinadad	9		0.5	1959
Limestone	Ockenden, England	13	330		
Limestone	Rugby, England	92	250	1.5	1964
Limestone	Calaveras, California, U.S.A.	27	180	1.4	1971
Limestone	Australia	96		0.4	
Kaolin	Georgia, U.S.A.	110	450	0.5	
Kaolin	Georgia, U.S.A.	18	200	0.3	1951
Kaolin	Georgia, U.S.A.	26	200	0.4	1959
Phosphate Rock	Valep, Brazil	113	200	2	1979
Gilsonite	Utah, U.S.A.	116	150	0.4	1957
Copper tailings	Japan	64	200	0.9	1968
Gold tailings	South Africa	148	150 & 230	1.0	
Gold tailings	South Africa	19	150	0.9	
Gold tailings	South Africa	15	230	0.9	
Gold tailings	South Africa	10	200	0.5	
Gold tailings	South Africa	10	150	0.2	

5. SLURRY PREPARATION

by

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Phillips Barret Kaiser

5.1 PURPOSE AND SCOPE

The objective in preparing a liquid- solid slurry for pipelining is to take granular solids and combine them with appropriate amounts of water so that they can be stored, reclaimed and handled with ease. Production of the slurry in a form suitable for pumping, whether short or long distances, is the desired output. Proper design of the slurry preparation facility includes process design and equipment selection based upon the desired slurry characteristics and the feed solids size distribution and characteristics. If the solids are produced from a hydraulic mine or cleaned in a preparation plant, some of the slurry preparation steps can be eliminated.

5.2 SLURRY PUMPING CHARACTERISTICS

Slurry pipelining of solids like any other transportation system is simply a means to move the production from the mine to the user in the most economical manner possible. Development of the slurry pumping system requires the close interrelation of the mine operation, beneficiation and desired end utilization characteristics. Regardless of whether the system is short distance (less than 10 km) or long distance (over 10 km), similar design considerations and determinations should be made. Much of the past experience with long distance pipelines has been pumping coal at a fine size, minus 1.18 mm (14 mesh). Fine coal pumping, while necessary for the operation of the pipeline, may have a negative effect on the coal quality for the user. Degradation and oxidation are two of these effects.

Degradation of particles can increase the ratio of ultra fines (less than 0.05 mm) to the point that the user will need to classify out a portion prior to utilization. Prolonged contact with a high oxygen content carrying fluid can cause oxidation of the surface, lowering the net heating value. Overall system results can be improved by starting with a coarser feed and allowing for those effects. Fine coal pipelining is expensive in terms of power and equipment at the slurry preparation end (Ref. 1,2). A key ingredient in designing a slurry preparation facility is the balancing of the slurry pumping characteristics, the desired end use characteristics, and the as-mined characteristics. The recent trend has been to pump a coal slurry at coarser sizes (Ref. 1,3). While this has some negative impacts on the energy efficiency and the corrosion and abrasion characteristics of the pipeline, the net energy loss for the overall system is reduced. Experience has shown that the overall net energy loss of the system is more critical to the economics than the selection of the optimal pipeline characteristics, especially for short pipelines. Several pipeline projects have been cancelled due to poor economics, but none from inability to produce a pumpable slurry.

If the total energy requirements for pumping exceed grinding and dewatering energy requirements, consideration should be given to fine size slurries. On the other hand, if grinding and dewatering energy requirements exceed those of pumping, a coarse slurry may be advantageous.

Many items impact on the design and operation of the slurry preparation system. These include particle size distribution, solids concentration, water pH, oxygen or air content of the slurry, chemical interaction between the solids and any agents necessary to sustain proper flow, the capacity desired of the pipeline, the capacity of the coal handling system feeding the plant and others (Ref. 2,4). These items fall into two general areas; physical attributes of the solids-liquid-mixture, and the physical and chemical interaction of the resultant slurry on the system. Those factors that relate to the slurry reacting on its system (water pH, air content, chemical interaction, abrasion corrosion, etc.) can be handled by proper selection of materials for the system construction. Particle size distribution, pulp density both of feed and product, and desired pipeline capacity become involved with the process design and equipment layout.

5.2.1 Particle Size Distribution

The relationship of the feed particle size distribution to product particle size distribution for the pipeline is a direct measure of the amount of energy necessary for the slurry preparation process. The closer these two are together, the less energy intensive the process will be. Primary energy use for slurry preparation is the comminution stage, which accounts for 50(+)% of the energy.

Design and sizing of comminution equipment is more complex than can be covered in the scope of this section. The interested reader is directed to minerals beneficiation handbooks such as *Principles of Minerals Dressing* by Gaudin, McGraw-Hill, or *Handbook of Mineral Dressing* by Taggert, J.F. Wiley & Sons. These handbooks and others can supply the details to design and size of the equipment. Early pipeline design assumed that the finest grind available would give the best performance. This would be true if the pipeline was a stand alone system. But as size consist is integrated with the mine, preparation facility, pipeline, and final user, more than just the pipeline and pipeline efficiency must be considered. Studies have indicated that particles of approximately two mm in size require the maximum power per km. For uniform mixtures coarser and finer than this size, the horsepower requirement actually will decrease. Design studies have been based also on the fact that pulverizing the coal prior to pipelining would eliminate the cost of pulverizing at the other end; but the finer the coal the more difficult it is to dewater, which often is incrementally as expensive, if not more so, than pulverizing. No specific solutions can be given without taking into account each unique pipeline and pipeline arrangement. A general statement can be made that the coarser the particle size being pumped, the lower the overall cost of the system, because of decreased grinding costs at the feed end and decreased dewatering cost on the receiving end.

5.2.2 Solids Concentration

The solids concentration of the slurry will affect the flow properties in the system. Concentrations of up to 70% by weight of coal in water have been successfully handled for short distances (up to 50 miles) (Ref. 1,3,4). Again, as with the particle size distribution, the pulp density can be adjusted to a desired level. Common experience indicates for extremely coarse slurries, 100 mm topsize, slurry concentrations of 30 to 40% may be optimal. For finer sizes, 0.15 or 0.075 mm topsize, slurry concentrations of 60 to 70% by weight are feasible (Ref. 2,4). At 60 to 70% weight these become coal slurry fuels and may be burned directly without further processing, if the receiving facility has that capability. Generally, the diameter of pipelines decrease and the capital costs become lower as the slurry concentration is increased in design studies. Off-setting this, the operating cost becomes higher as the viscosity of the slurry increases. It also increases as the average particle size increases, as coarse solids require higher velocities to remain suspended.

5.2.3 Pipeline Capacity

The desired throughput of the pipeline and its operating conditions have a very significant impact on the slurry preparation facility. Most coal production facilities, i.e., coal mines, do not run 24 hours a day 7 days a week under current practice. A more common operating schedule would have allowances for non-operating availability due to shutdowns and other emergencies. It is necessary to match the pipeline slurry preparation facility with both a non-continuous operating mine and a continuous operating pipeline by carefully matching the appropriate and optimal size facility. The variations between mine production and plant capacity are handled by both a raw coal and a prepared slurry surge capacity. The raw coal surge can be handled through stockpiles or silos while the prepared slurry surge is handled through surge tanks and storage tanks. Consideration must be made to prevent settling of the coal in the storage tanks. And thus minimal surge on the pipeline side should be maintained. Some surge capacity on the pipeline side is achieved through required agitation and mixing tanks to prepare the slurry to the desired concentration.

5.3 COMPONENTS OF A SLURRY PREPARATION FACILITY

A slurry preparation facility will have the equipment necessary to receive and store solid material, prepare the solid to the desired pipeline characteristics (particle size distribution), mix the solid with water, and store the resultant slurry prior to pumping. Also, the first pumping station normally is included with the slurry preparation facility.

5.3.1 Receiving, Storage and Handling

The storage and handling facility will vary depending on the plant location. If the plant is co-located with the mine and there is a beneficiation plant present, minimal receiving and storage facilities are required. At this point only a surge capacity to handle operational fluctuations at known plant downtimes would be required. If the slurry preparation facility is separate from the mine site, then a receiving station for either trucks, rail or conveyor belt will be needed, followed by a storage facility to handle the surge loading from the transportation system and to feed into the processing plant at the desired rate. Storage and handling facilities are normally sized on the basis of supplying at least one shift operational capacity ahead of the plant for closely coupled operation and two to three days storage for discontinuous operations. If the plant is near or part of the beneficiation facility, the feed may be coming to the plant in a wet condition and some preliminary sizing and processing would be done on the site with no surge capacity ahead of the slurry preparation facility. In this case all surge capacity would follow the slurry preparation and be prior to the pipeline. The factors that directly affect the storage and handling facility and the design of them include the moisture content of the solids, the size range of the solids, and whether the solid material has been cleaned.

5.3.2 Slurry Preparation

Converting the mined solids into a slurry pipeline feed stock is in essence a size reduction step followed by a

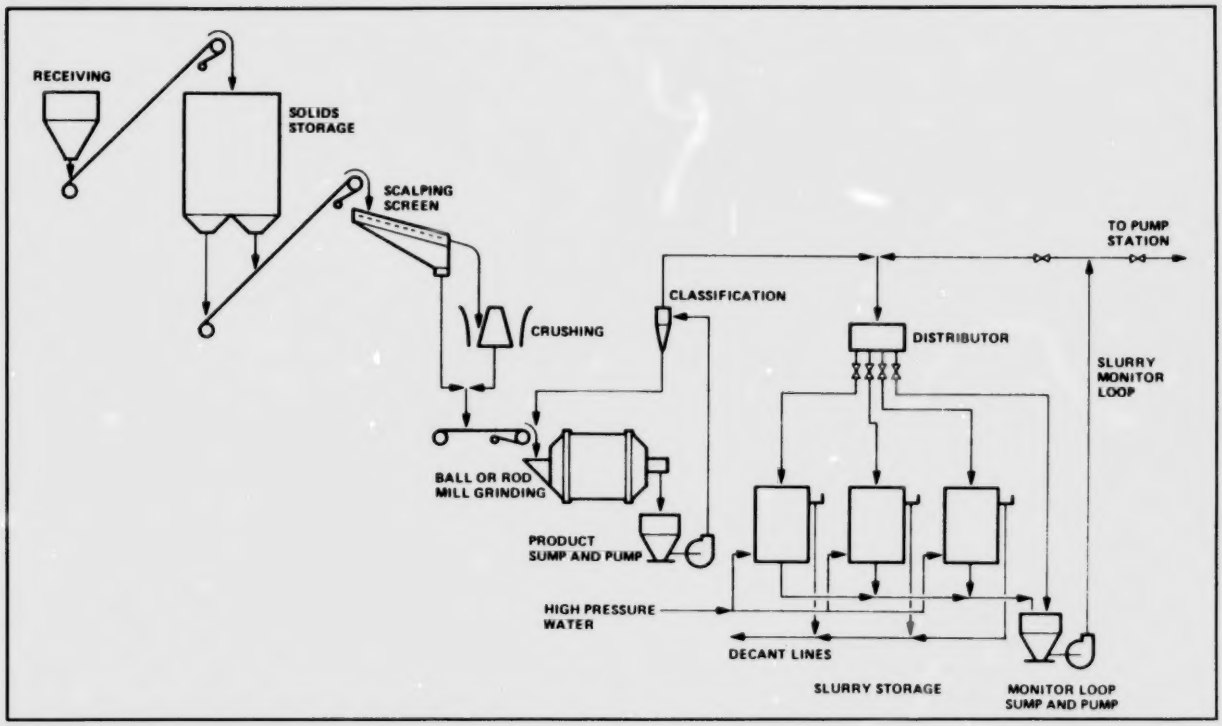

Figure 5-1. Typical slurry preparation facility

mixing step. With the utilization of ball mills or rod mills for the size reduction for fine feed, the mixing step can be combined easily with the size reduction. Selection of appropriate equipment is based on ratio of feed size to end product size (pipeline feed). Each stage of size reduction is limited generally to a ratio of 4 to 1 (e.g., for 100 mm feed the product size would be 25 mm). For more details, the interested reader is referred again to the mineral dressing handbooks mentioned in Section 5.2.1. If it is desired to pipeline as coarse feed stock as possible, up to 25 mm (1 inch), size reduction would be followed by screening out of the plus 25 mm (1 inch). The reduced material then will be discharged into a sump and water will be added and recirculation maintained until the desired pulp concentration is reached. This pulp could be pumped then to the storage facility or to the pipeline pump station. A general flowsheet for a slurry preparation facility is shown in Figure 5-1. In this flowsheet the new feed from the mine is screened, crushed to 12.5 mm (½ inch) topsize, and combined with water and recirculating coal slurry from the monitor loop of the pipeline pump station. This coal-water slurry flows to a distributor and is distributed alternately to one of several collection storage tanks. Two possible alternative operations are maintained for these tanks; the simplest has the tanks sized large enough to allow the solids to settle, and a supernatant liquid to collect on top and be drawn off. Each tank in the other concept will be sized similarly but would have an agitation mixer in the centre and a recirculation pump to pump carrier fluid around the coal. The coal is drawn off from the bottom and pumped to a distribution monitor tank, from where it is pumped to a monitor loop to check and maintain the required slurry characteristics. If the characteristics are as desired, it is pumped to the first pipeline pump station. If the characteristics need to be changed it is pumped back to the storage tank. A constant stream is returned as recirculation to the distributor and to the storage tanks.

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6. SLURRY PUMPS

by

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6.1 PURPOSE AND SCOPE

Pumps which are used to move a slurry in a pipeline may be of several types. Centrifugal and reciprocating pumps usually are employed; however, other types such as diaphragm, Moyno, surge leg, oil/slurry interface, lockhoppers, jet pumps, and air lifts can be considered. Each has limitations and may be fitted into systems in which their particular characteristics may justify the selection. This chapter emphasizes those factors which should be considered when applying centrifugal or reciprocating pumps for pipeline service.

6.2 CENTRIFUGAL SLURRY PUMPS

Centrifugal pumps have been used for a long time as sand or dredge pumps and for mine tailings transfer. With this background of experience, these pumps have been developed to be wear resistant and have the capability to provide economic performance for the transport of slurries. They have been used widely in plant systems and in long distance slurry lines as suction charging pumps to large reciprocating mainline pumps.

6.2.1 Centrifugal Pump Design

The centrifugal pump is a hydrokinetic device where an increase in velocity in the fluid moving through the impeller is converted to head. To achieve high heads, large changes in fluid velocity are required and by the abrasive nature of slurries, pump designs must accordingly be limited to internal velocities which will yield tolerable attrition rates. The wear resistant capability of centrifugal slurry pumps is provided by the use of rubber or elastomer linings, which are replaceable, and coated impellers. In other configurations, hard metal casings or linings are used. They are designed in a single stage to allow removal of the components.

Rubber lined pumps usually are limited to fine slurries having a maximum particle size of 2.4 mm (eight mesh). The impeller tip speed is limited generally to the range of 20-22 m/s (4000-4400 fpm), thus limiting the discharge head that can be generated. Metal lined pumps are used to handle coarser particles. With a higher tip speed generally allowed, higher heads can be generated. Heads are limited to 24-40 m (80 - 130 feet) per stage, depending upon the slurry service. This will require generally more than one pump to be installed in series. As many as six pumps can be considered in one pumping system, but the limitation is set by the casing design pressure. Therefore, for all practical purposes, centrifugal pumps are limited to short distance pipelines, typically in the range of 10 km (6 mi) or less.

Some designers recommend that an extra pump should be provided as a standby so that if one of the pumps becomes disabled it would be possible to bypass it and still maintain the system design conditions. However, some operators warn that the valves required are not reliable enough, for certain slurries, to make such a system economical. They recommend that if a pump fails, the line should be flushed and a spare pump installed in place of the failed pump.

6.2.2 Seal Flush

As a general rule, centrifugal pumps are provided with a seal water flush as a means to keep the gland packing clear of solids and to provide for cooling of the packing. Seal flush volume, typically one to three percent of pump discharge volume, has the effect of diluting the slurry. The system designer must include consideration of its effect in the pipeline design. An adequate seal water pressure should be provided in a multiple pump station to allow for varying pressure conditions within each stage. A mechanical type seal also is available which utilizes an expeller design. In this case, seal flush liquid is not required.

6.2.3 Centrifugal Pump Efficiency

The efficiency of a centrifugal slurry pump is generally fairly low due to design compromises to allow for minimizing abrasion by the slurry and to increase the sizes of flow passages and clearances. Efficiency values are typically in the neighborhood of 65 percent. However, the actual efficiency of the pump being considered must be taken into account in the design of the pumping system.

6.2.4 Centrifugal Pump Characteristics

The performance of the centrifugal pump is of particular interest. Figure 6-1 describes the fairly flat head curve over a wide flow range. For this reason, a small

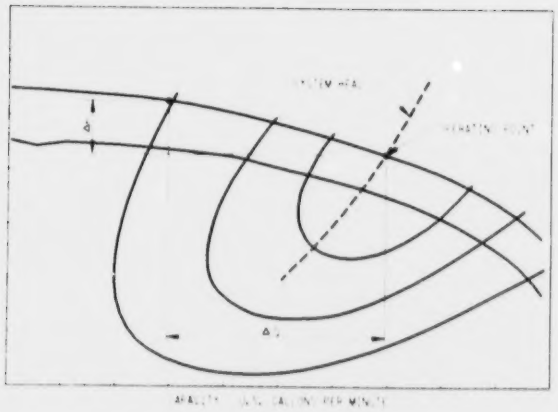

Figure 6-1. Typical head capacity curve – centrifugal pump

increase in head can result in a rather substantial drop-off in flow. If a restriction to flow develops in the pipeline due, say to settling of solids in the slurry, increased pressure will be required for flow through the reduced flow passage. This can produce a worsening condition as the pump provides reduced flow and thus more dropping out of solids. The designer can offset this condition by providing a variable speed drive to the pump so that speed may be increased to maintain the desired line flowrate.

An interesting characteristic of centrifugal pumps is that they only produce head, while the pipeline depends upon system pressure. Referring again to Figure 6-1, the system head (pressure) is the summation of the discharge head required to move a given throughput of slurry in the pipeline as a result of the hydraulic gradients due to the changing elevation of the pipeline and the flow friction head as a result of the slurry characteristics. The slurry will exhibit an apparent viscosity which affects the friction head and this is influenced by the density, the consistency, and the distribution of the particle sizes.

These considerations make the slurry pump sensitive to proper sizing and powering, considering the possibilities of these transient flow conditions which may result in mismatching of the pump to the pipeline. Further, it becomes very important for the system designer to provide for changes from slurry to water, occasioned by dropout, line start-up, or batching of slurry and water intermittently.

6.2.5 Summary

Centrifugal pumps have a relatively low capital cost and require limited space in the pump station. High flowrates can be put through a single unit with flowrates of 5700 m^3 hr (25,000 gpm) possible. The number of replacement parts is limited primarily to the casing liner, impeller, gland packing and wear sleeve. They are simple to operate as well as to maintain. Fairly large particles can be handled. There are no flow pulsations. They have no valving within for operation. The prime disadvantages are that they are pressure limited as to performance and

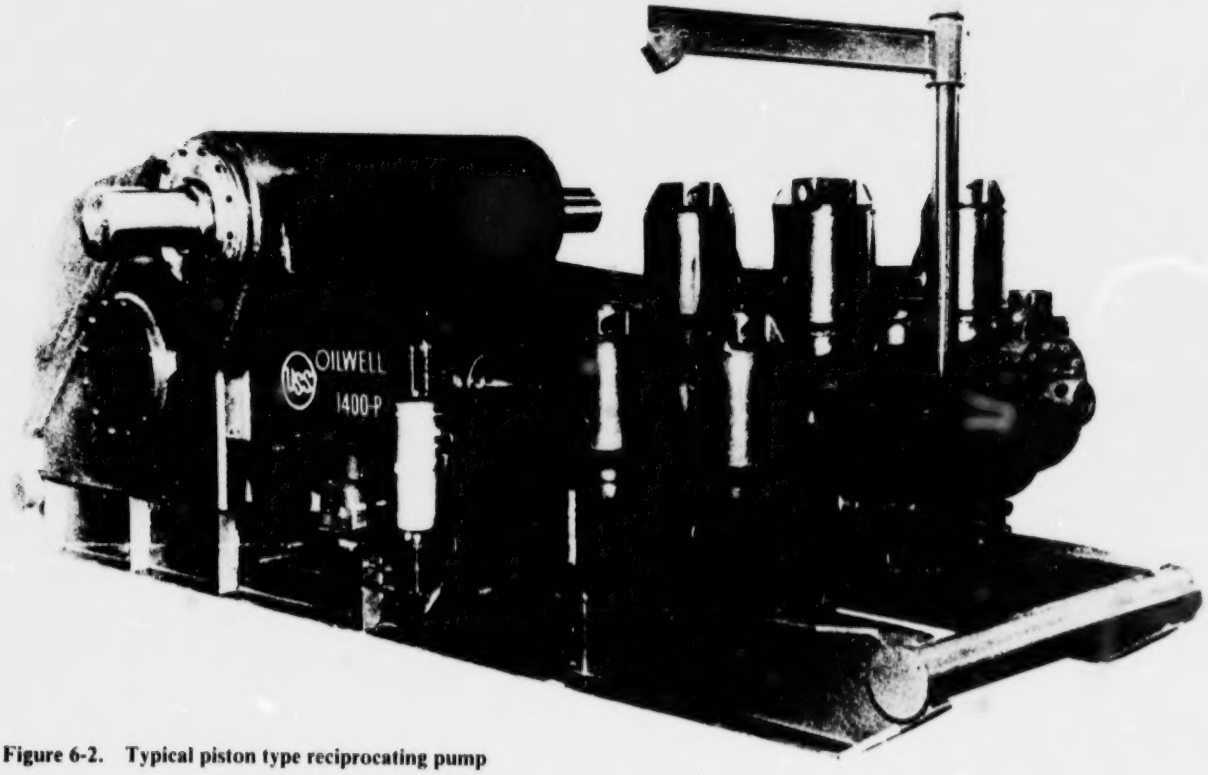

Figure 6-2. Typical piston type reciprocating pump

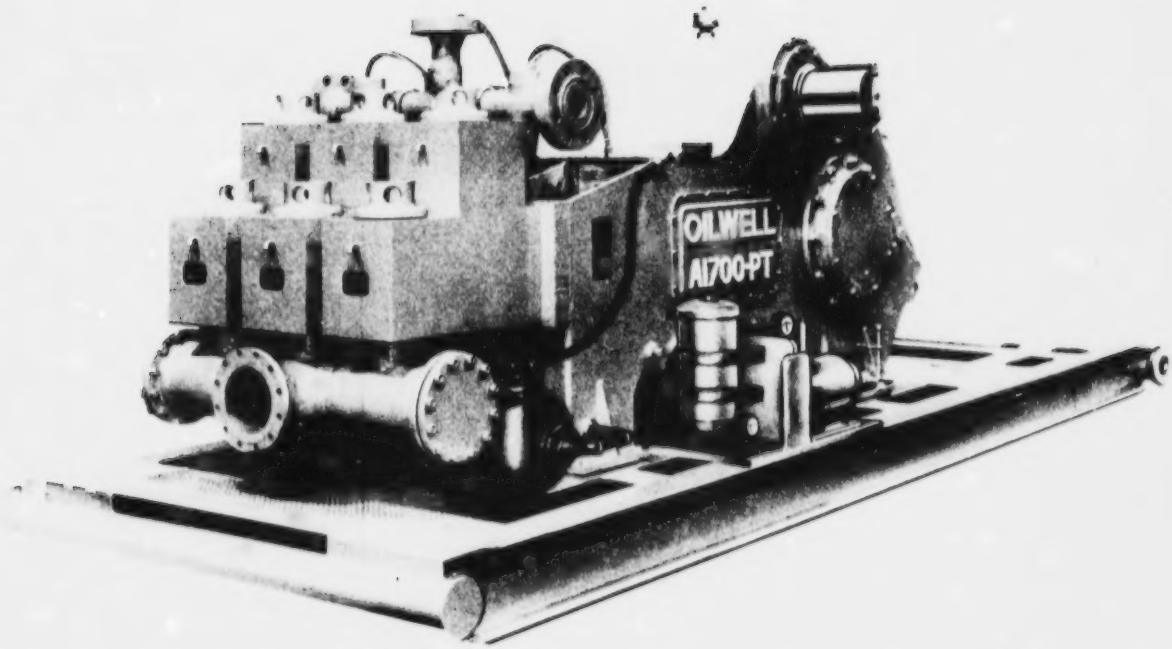

Figure 6-3. Single acting piston type reciprocating pump

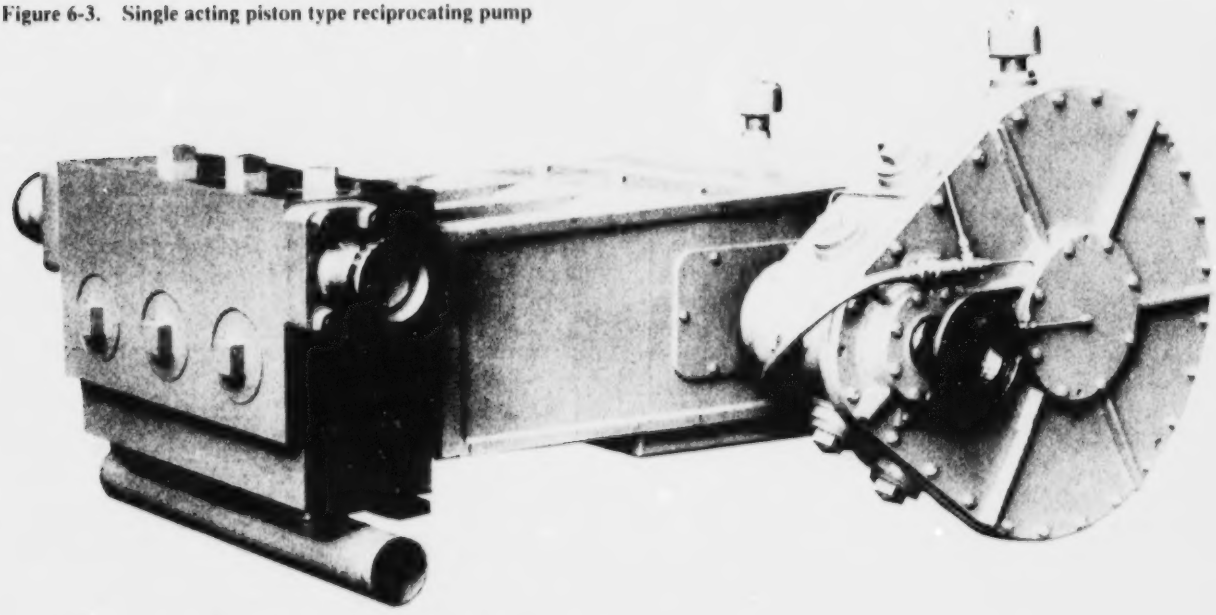

Figure 6-4. Light weight triplex single acting type reciprocating pump

by casing design; the flow is governed by system pressure; internal deterioration is due to velocities enountered within the pump; and seal water flush can cause undesired dilution.

6.3 RECIPROCATING SLURRY PUMPS

Reciprocating slurry pumps are generally of the piston type which have been used for many years as slush pumps in the oil well drilling industry. See Figure 6-2. Triplex, double-acting pumps also have been used. These piston type slurry pumps have specially developed liquid end parts designed to resist the attritional effects of abrasives. Although drilling pressures of 27,600 kPa (4000 psi) have been met satisfactorily with duplex piston pumps, for pressures above 13,800 kPa (2000 psi) single-acting type pumps have been more widely used in recent years. See Figure 6-3. Single-acting triplex pumps of light weight design have been used for many years to handle cement and sand slurries in oil well cementing and fracturing services. See Figure 6-4.

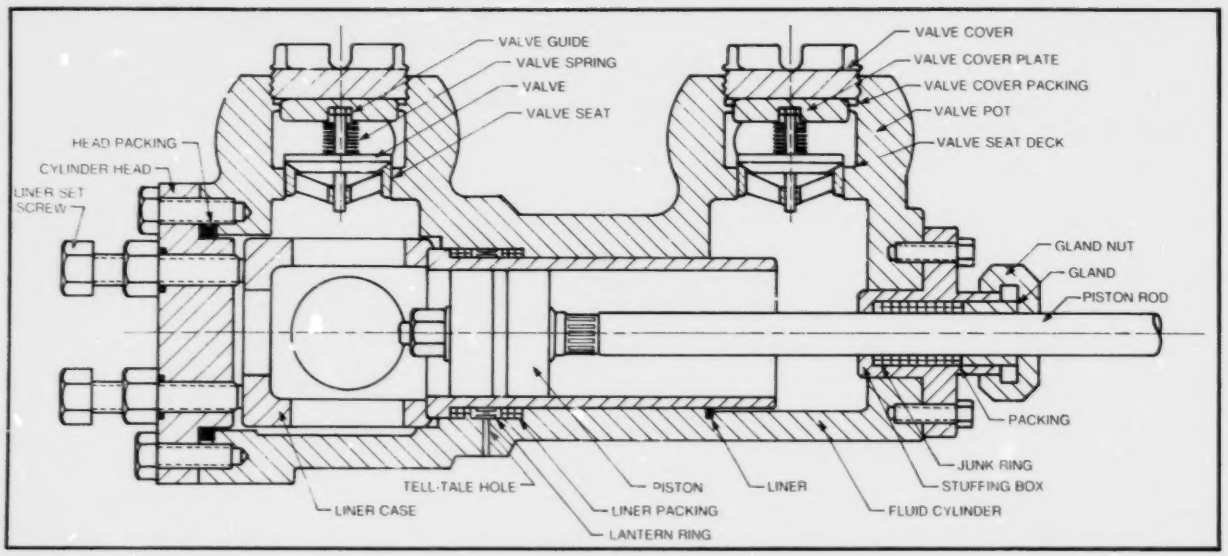

Figure 6-5. Cross section – typical single acting plunger type slurry pump

6.3.1 Piston or Plunger Type

Two basic approaches are utilized in the handling of slurries with reciprocating pumps. In one case, the direct action of the displacement member is in the liquid end, and in the other case, a clean liquid barrier is provided between the abrasive liquid and the sealing element.

When should piston type, double-acting, positive displacement pumps be preferred over plunger type, single-acting pumps? Referring to Figure 6-5, consider the piston rod thrust as delivered to the piston area. For a given rod loading, the area of the piston will be large for a low discharge pressure and small for a high discharge pressure. As the piston diameter is reduced, the head-end displacement volume also is correspondingly reduced, but the crank-end volume is reduced even further since the piston rod then becomes an appreciable part of the crank-end volume. Thus the design begins to approach a plunger pump. With the volume variation of head-end to crank-end and the overlapping phases of pump cylinder displacement, the fluctuation in the discharge rate may be great. However, properly designed and applied reciprocating pumps using good discharge pulsation dampeners and suction flow stabilizers will allow one to live with the varying flowrate.

6.3.2 Plunger Flush

In plunger pumps a liquid seal is created by an injection of water, or other appropriate liquid, ahead of the plunger packing in such a way that the packing contacts no abrasive liquid. See Figure 6-6. A flush volume of three to five percent of discharge volume is required to provide an adequate circumferential counterflow to be effective. As with centrifugal pumps, the packing flush dilutes the slurry and the system designer must consider its effect downstream.

6.3.3 Slurry Valving

The valves of plunger and piston-fitted reciprocating pumps must operate in the slurry at all times. One cannot isolate the valves from the slurry in any now known positive displacement pump design. Therefore, the valve is probably the most important liquid end part to be considered.

A slurry valve must have two fundamental characteristics. It must be of sufficient strength to resist the load imposed by the fluid pressure above it and, secondly, it must be able to seal against this pressure in the presence of

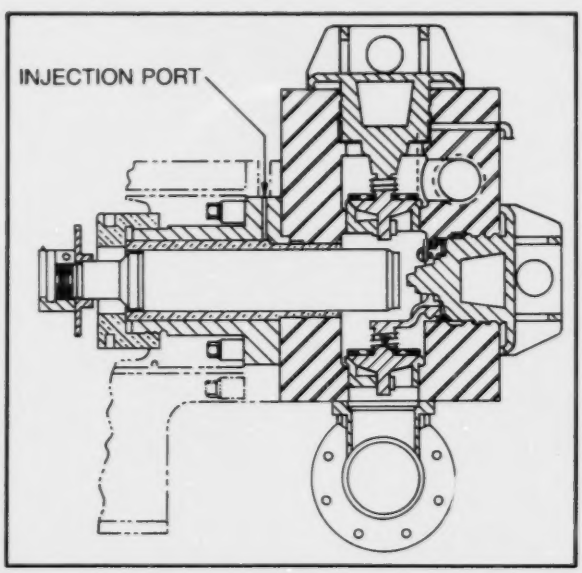

Figure 6-6. Cross section – typical single acting plunger type slurry pump showing plunger flush injection port

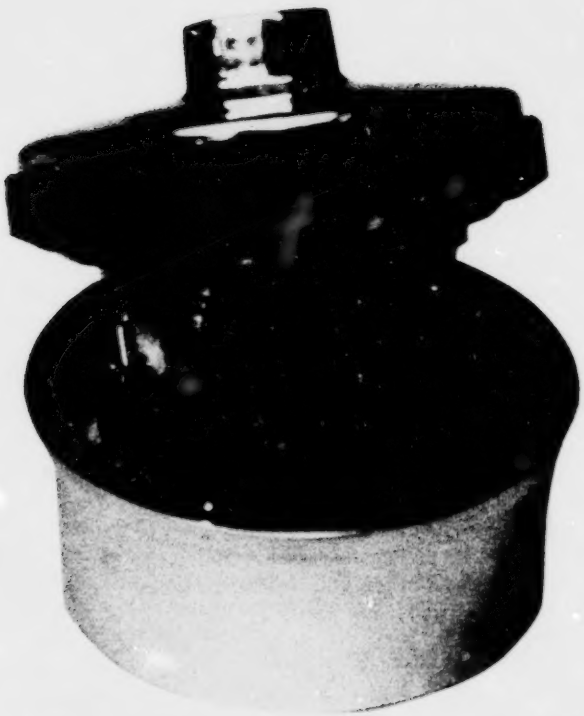

Figure 6-7. Typical valve and valve seat for reciprocating pump

solid particles of various sizes. To provide adequate supporting means for the pressure load, there must be a sufficient metal-to-metal bearing area in the valve seat. One problem exists as the amount of area is increased to provide more support. The reduction of flow-through area in the valve affects pump performance. In general, the fluid velocity must be limited through a valve because of the erosion that results with higher velocities. This results in limiting the bearing area between the valve and the seat.

Valve seats are made with cylindrical openings where wing-guided valves are used. See Figure 6-7. But more widely used is a valve seat which has provision for a stem guide on the valve. This is accomplished by the provision of ribs, or a "crow's foot". See Figure 6-8. The ribs provide a bridging type support to the valve plate surface. This valve design has functioned very satisfactorily in the handling of coal slurries.

The elastomer bears on the outer beveled edge and the plate portion of the valve rests upon the ribs. See Figure 6-9. In the centre portion of the seat, a relief under the valve is provided to allow clearance for particles. This clearance is designed to prevent "jamming" of particles between the guide and stem. This valve is stem guided, both top and bottom, so the upward and downward movement of the valve progresses in a controlled motion. This keeps the valve centred to the seat. Both the upper and lower stem function within elastomer lined bushings to resist abrasive wear.

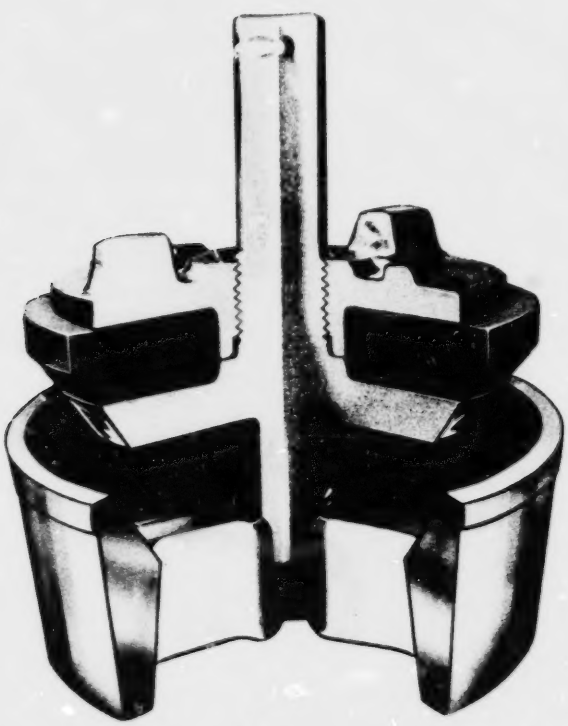

Figure 6-8. Cut away – stem guided valve and valve seat for reciprocating pump

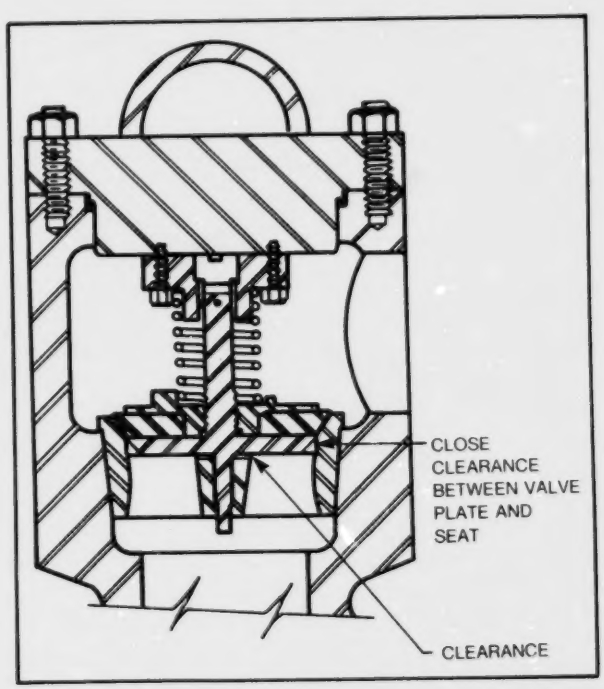

Figure 6-9. Cross section – stem guided rib type slurry valve

A true rib-supported valve actually requires a flexible seal because it would be impossible to obtain a seal at the metal-to-metal tapered faces and simultaneously seat on the ribs. To seal properly, the elastomer must be in such a position as to cover particles which might be entrapped on the sealing faces.

The wearing rates of the elastomer-to-metal and the metal-to-metal surfaces at the rib contact are not uniform and thus it is necessary that there be some compliance.

Another advantage of the rib-supported valve is the "built-in" filtering action that tends to strain out the larger particles just before the valve closes. In this valve, still referring to Figure 6-9, the piston shape of the valve proper entering a close cylindrical closure, just before closing, traps out larger particles and the elastomer has a better chance of sealing against a "cleaner" fluid. However, this type of valve can only be used when a low degree of abrasivity is present and the particles are fairly friable.

For extremely abrasive, finely divided materials, more metal-to-metal bearing area and less elastomer are desirable.

It has been found that the weight of the valve is not as critical as one might expect, because a valve is not "slammed" shut. Its motion follows the sinusoidal displacement pattern of the piston (or plunger), thus allowing for a gentle opening and closing. However, with inadequate suction conditions, violent behavior of a suction valve may occur with consequent destructive effects.

6.3.4 Pistons and Liners

In a piston pump the piston which displaces the fluid runs in a renewable metal cylinder or liner. The piston rod runs through its packing and presents a second point of sealing and wear. In the case of a single acting pump, the plunger with its packing presents the only comparable point of wear.

A typical slurry pump piston with a portion cut away to reveal construction details is shown in Figure 6-10. The piston elements are separate from the hub member and they are retained by end washers and retaining rings. The piston is so constructed as to have three basic elements: the sealing elastomer, the fabric section, and a back-up metal plate section. Under hydraulic loading, the "rubber" is pushed back against the fabric section and out against the liner to form a seal. The fabric section provides extrusion clearance control and the metal back-up plate provides the structural capacity to hold the piston load.

The liners used are made of abrasion and corrosion resistant metals which have been found in extensive service to resist wear for specific slurries.

Piston rods and plungers are usually coated with similarly suited materials for the same objectives while retaining base metal characteristics for the required mechanical loads in the parts.

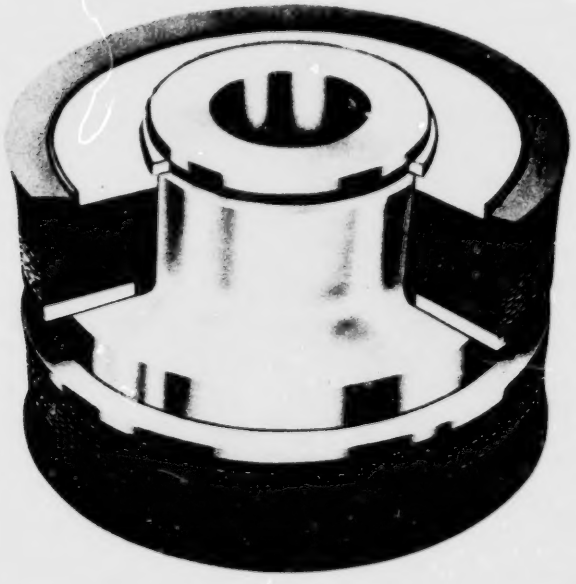

Figure 6-10. Cut away - typical slurry pump piston

6.3.5 Packings

Packings present some rather subtle considerations in the design of both piston and plunger type slurry pumps. "Nonadjustable" type of lip packing gives superior service. The nonadjustable feature eliminates the tightening required with softer lip packing, such as the ordinary V- or chevron- type packings. Soft, full section packings should be avoided as they are not satisfactory. There is a tendency for abrasives to enter the sealing surface and if the abrasive is imbedded in the packing, a grinding lap occurs which greatly accelerates the wear of the metal surfaces on the rod or plunger. Uncut rings of packing are preferable to cut rings because of the leakage problem at the mating joint. However, cut rings are frequently used for rod packing on piston pumps because of the ease of installation.

There is a distinctly different behavior between the rod packing in a piston pump and plunger packing in a single-acting pump. Consider the use of lip-type packings for both designs. The lips acting on a piston rod are so disposed that they point toward the piston as it moves away during the suction stroke, whereas in a plunger pump just the reverse is true. See Figure 6-11. The plunger moves toward the lips during the suction stroke. Under suction conditions the lips are relaxed because of the lack of sealing pressure to hold them tightly against the metal surface. In the case of the plunger pump, abrasives can enter under the packing lips. When the packing lips are tight under pressure, they serve to scrape as well as seal off abrasive material at the same time. For these reasons it is necessary that a clean liquid interface be created between the packing and the abrasive liquid for satisfactory plunger pump service as has been previously described. One advantage of the plunger type construction is that it

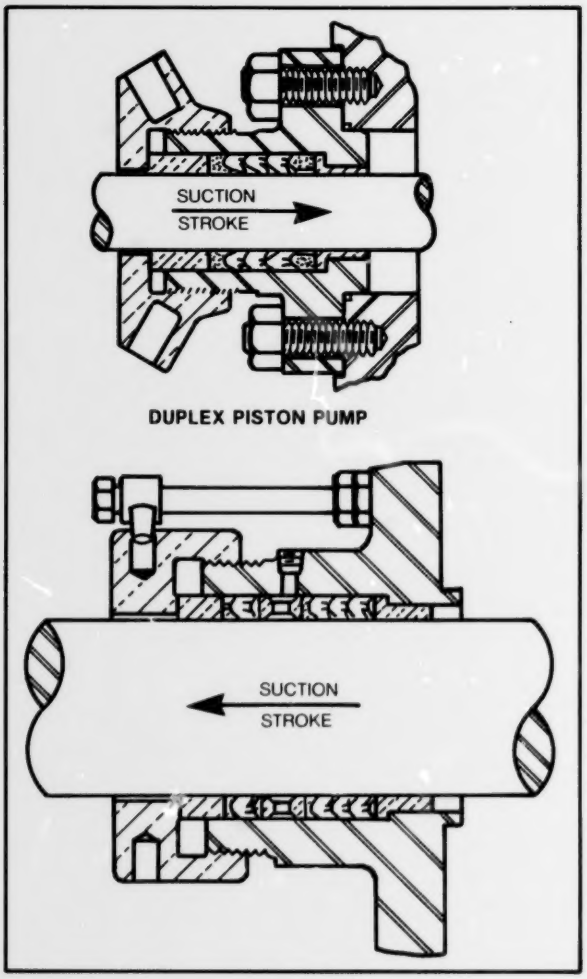

Figure 6-11. Cross sections - typical packing seals for piston plunger type slurry pumps

is possible to lubricate the plunger easily and the lubricant will carry into the packing assembly on the pressure stroke.

6.3.6 Characteristics

Reciprocating pumps have the desirable characteristic of maintaining a high volumetric efficiency at any desired flowrate. This allows a greater flexibility in system design. Because of positive displacement and high efficiency, these pumps can be used for metering station throughput. Reciprocating slurry pumps are designed to have easily and quickly replaced liquid end parts which are subject to the deteriorating effects of slurries.

6.4 SUMMARY

Another point of consideration is the proper selection of the reciprocating pump configuration for the service intended. Consider the pumping station in terms of the slurry being handled by the pumps, and the number of expendable liquid end parts which are functioning in the slurry. Keep them as few as possible, as they represent operating costs. The overall economics of the system are directly affected by the choice of pump configuration.

It is advisable for those who are responsible for system design and the selection of pumps to consult manufacturers of both centrifugal and reciprocating slurry pumps who possess a wide spectrum of experience. Much of the information regarding the fine points of pump design is proprietary, and it is recommended that the manufacturers be consulted before committing a choice of pumps to a pipeline. Engineering and construction companies have slurry pipeline design experience, and the operators of existing slurry pipelines have acquired considerable experience. No pump selection should be attempted without reaching for this experience.

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7. SLURRY FLOW PRINCIPLES

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7.1 INTRODUCTION

The physical laws governing single phase fluid flows have been well understood for over a century. Although digital computers have extended immeasurably our capacity to solve the partial differential equations with which flow situations are described, there are still innumerable single phase flow problems which remain to be solved. Many of these problems are geometrically complicated (three dimensional) and/or involve time as an important independent variable. However, even the simplest case of great engineering importance, macroscopically steady single phase flow in a pipe, cannot be regarded as fully understood in the turbulent region. Faced with this difficulty, the designer often must rely upon the results of experimental studies. Fortunately, these measurements can be generalized with dimensionless relationships, whose existence can be deduced from the physical laws. Thus engineering predictions for flows through pumps, valves, fittings and metering devices can be made with confidence for single phase flows.

For a two phase mixture, the number of independent variables is immediately doubled and the complexity of flow problems is further increased by the fact that conditions at a point are never truly time independent. For flows which are macroscopically steady, time-averaged equations of motion can be used to analyze flows in which fluid-particle drag interactions are of dominant importance. Such situations (sedimentation, fluidization, etc.) are invariably those for which drag forces at the system boundaries can be neglected, in contrast with the pipe flows which will be considered here.

Slurry flow phenomena are determined by the properties of the slurry and the conditions of the flow. Slurry properties depend upon characteristics of the particles (size, size distribution, shape and density), those of the fluid (viscosity and density) and the properties of the fluid-particle interface which are determined by the compositions of the fluid and the solids. Flow conditions depend upon the geometry (pipe or viscometer), history (steady flow or transient) and system variables (velocity, characteristic dimension and temperature). Because of the large number of variables, many of which cannot be varied independently in experimental studies, at present only a partial or imperfect classification of flow regimes is possible. Additional complications are that the qualitative descriptions of these flow regimes are rather indistinct and that the transitions between them are gradual.

Faced with this problem, the simplest course is to describe limiting cases or flow regimes which are clearly distinctive. Actual slurry flows will fall somewhere between these cases and part of the function of further research is to improve predictions for these actual flows. The limiting cases, on the other hand, are much more fully understood.

Liquid flows are either laminar or turbulent and the difference between them can be established in a variety of ways. Although the laminar or turbulent distinction is important for slurries, it is less critical than differences which arise from the fact that two phases are present. Thus for slurries, it is the extent to which the mixture resembles a true liquid which is of primary importance. Three limiting cases can be identified to reflect behaviour which is:

a) essentially identical to liquid flow (homogeneous flow),
b) having some similarity to liquid flows (pseudo-homogeneous flows),
c) profoundly different from liquid flows (segregated flows).

This classification reflects the importance of the distribution of the particles within the flow field. This distribution depends upon the balance of forces acting on the particles, a subject of which understanding remains incomplete. Progress in this area is essential if reliable predictions are to be made for actual slurry flows.

7.2 HOMOGENEOUS FLOWS

Homogeneous flows are those of homogeneous slurries which, by definition, show no segregation under any circumstance. In this respect the slurry resembles a true solution, for which the science of rheology has been well developed. Usually the resistance to flow or effective viscosity is high for homogeneous slurries and pipeline flows may be either laminar or turbulent.

The major technical problem for homogeneous slurries is prediction of pressure drops for laminar and

turbulent flow, and the transition point between them. For such slurries, viscometric characterization is possible (and essential). Although other viscometric flows can be used, tube flow has the advantage that the transition between laminar and turbulent flow can be determined experimentally in the appropriate geometry. Other considerations which determine the type of viscometric test are discussed in Chapter 10.

To achieve the truly homogeneous slurry condition, a substantial degree of subdivision of the solid phase is required, with a correspondingly high interfacial surface area per unit slurry volume. This large area, combined with forces of attraction between particles, accounts for the internal slurry structure which resists settling even on standing in a quiescent condition. This structure can also account for the shear dependent and/or time dependent resistance to flow which is called non-Newtonian behaviour.

For homogeneous slurries the approach is:

a) determine an appropriate rheological model from a test program and evaluate the specific coefficients for the slurry at the temperature and concentration of interest,
b) find the head loss for particular velocities using piping system parameters.

A yield-power law model of the form

$$\dot{\gamma} = [(\tau - \tau_y)/K]^{\frac{1}{n}} \qquad ...7.1$$

often provides a very good fit of test data. τ_y is the yield stress, n is a dimensionless flow behaviour index and K is the consistency. For most slurries the Bingham model (n=1, K=μ_p) is adequate. The latter has the advantage of simplicity in the relationship between wall shear stress and velocity for laminar tube flow.

$$8V/D = \tau_o[1-(4\tau_y/3\tau_o) + (\tau_y/\tau_o)^4/3]/\mu_p \qquad ...7.2$$

where the wall shear stress is related to the frictional hydraulic gradient i by

$$\tau_o = i\rho_f g D/4 \qquad ...7.3$$

The hydraulic gradient, expressed in metres of carrier fluid per metre of pipe, is provided by the combined axial pressure drop and the pipe inclination effect.

$$i = -(dp/dx)/\rho_f g - \sin\theta \qquad ...7.4$$

where θ is the angle of inclination (upwards) of the pipe to the horizontal plane.

Equation 7.2 assumes only that the flow is steady, laminar and fully developed. Because of the approximation in the Bingham model, τ_y and μ_p should be determined at values of τ_o close to those applying in the actual pipeline. Within this restriction, Equation 7.2 is completely reliable in laminar flow and the practical difficulties are essentially those involved in determining τ_y and μ_p, as described in Chapter 10. Equation 7.2 may be expressed in terms of the friction factor defined by

$$\tau_o = fV^2/2 \qquad ...7.5$$

For convenience, the laminar flow f vs Re (=$DV\rho/\mu_p$) relationship is expressed in terms of the Hedstrom number parameter (He = $\rho D^2\tau_y/\mu_p^2$) rather than (τ_y/τ_o). f is always strongly dependent upon Reynolds number in the laminar region. Figure 7.1 shows the f-Re-He relationship for laminar and turbulent flow.

Turbulent flow of homogeneous slurries is a more difficult problem than laminar flow. It is known that f becomes much less dependent upon Re in this region, just as it does for Newtonian liquids. However, the value of f is still subject to some controversy. Although there are well documented instances of friction reduction (lower f than the Newtonian value), the evidence is not conclusive. It is possible that in turbulent flows additional factors enter the f-Re-He relationship and for this reason caution is advisable.

Hanks' (Ref. 1) semi-theoretical predictions are incorporated in Figure 7-1 and these can be used when direct experimental measurements are unavailable. A sample calculation illustrating use of this chart is given in Appendix 7-1.

If a power law model is to be used, the preferable form is the Metzner and Reed laminar tube flow relationship

$$(8V/D)^{n'} = \tau_o/K' \qquad ...7.6$$

n′ and K′ should be determined from laminar flow tests conducted at stresses close to those encountered at the wall of any operating pipeline. For the turbulent region, Dodge and Metzner have provided predictions of the friction factor (and the transition) for use in Equation 7.5. These are shown in Figure 7-2. n′ and K′ are defined in Equation 7.6. They are related to the constants n and K which appear in Equation 7.1. The relationship between these coefficients, as long as the shear stress range similarity is maintained, is

$$n' = n$$

$$K' = K[(3n' + 1)/4n']^{n'}$$

Occasionally, experimental data are used to determine an effective viscosity in the turbulent flow region. Experimental i values are converted to τ_o values with Equation 7.3 and these are used to determine f values from Equation 7.5. These values can be used then to determine the Reynolds numbers, from an f-Re correlation for homogeneous single phase flows. This procedure, which is used in Chapter 8, is permissible only if the slurry is homogeneous. With other slurries the effective viscosity

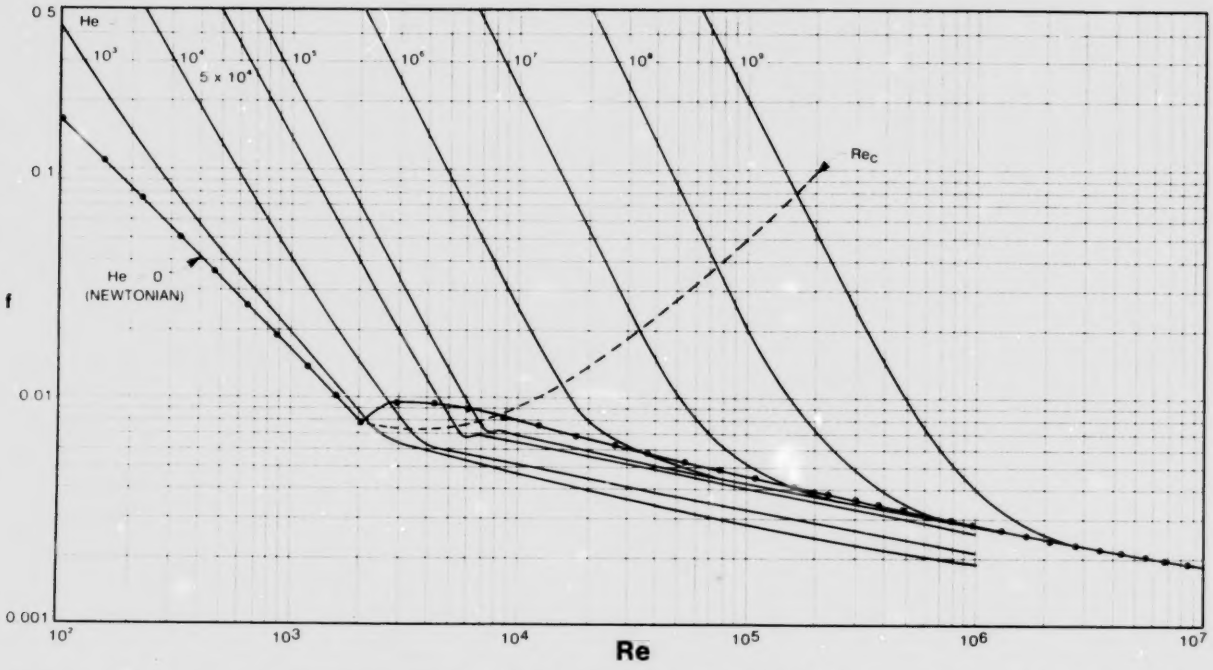

Figure 7-1. Design curves for Bingham plastic pipe flow. (by permission, from R.W. Hanks, Course Notes, Hydraulic Design for Flow of Complex Fluids, Orem, Utah, 1981.)

will appear to depend on pipe diameter and slurry viscosity, as well as with concentration, particle size, size distribution, shape etc.

7.3 PSEUDOHOMOGENEOUS FLOWS

As the settling tendency of a slurry increases, viscometric testing becomes progressively more difficult. However it is sometimes possible for such slurries to display head loss-velocity relationships which are similar to those of homogeneous slurries; such flows are pseudohomogeneous. In such cases the particle distribution is nearly uniform as a result of a strong mixing effect. An effective viscosity of the slurry may be deduced from the head losses using Equations 7.3, 7.5 and the Newtonian f-Re relationship. This viscosity is often lower than that which would be predicted from the bulk slurry concentration, possibly as a result of particle migration away from the pipe walls.

Pseudohomogeneous behaviour is revealed by testing programs, and it is fortunate that for a given slurry the tendency to show pseudohomogeneous flow increases as the pipe size increases. This means that a lower limit to the frictional head loss can always be estimated using the viscosity of the carrier fluid in the Reynolds number to evaluate the friction factor in Equation 7.5. The density in Equation 7.5 should be that of the slurry. Of course very high flow velocities may be required to produce pseudohomogeneous flow and these velocities may be far above the range of practical interest for the slurry if the settling tendency of the particles is high.

To predict whether pseudohomogeneous behaviour will occur, one would have to be able to predict the solids concentration distribution within the pipe. However, predicting the particle concentration as a function of position is difficult. For a dilute slurry of fine particles, a one-dimensional diffusion law can be used to describe the balance of gravitational and turbulent diffusion effects in the vertical direction:

$$\epsilon dC/dy + V_t = 0 \qquad ...7.7$$

Equation 7.7 is deceptively simple because for a pipe (with y measured upwards) ϵ should vary with position as well as with D and the friction velocity $(igD/4)^{0.5}$.

As the slurry concentration increases, the settling tendency decreases. Even if one replaces V_t by the hindered settling expression V_t', experimental results reveal that ϵ deviates progressively from the value predicted from fluid momentum exchange considerations. Some of this deviation is due to particle-particle interactions. As the particle settling tendency increases, the immersed weight is not borne completely by fluid lift forces but is transmitted in part to the wall by interparticle contact.

Equation 7.7 suggests that for slurries of fine particles the distribution becomes reasonably uniform at low values of the ratio $(V_t/(igD/4)^{0.5}$. This produces pseudohomogeneous flow. At very high settling tendencies the concentration distribution in a flowing mixture should approach that of a settled bed, with all the immersed

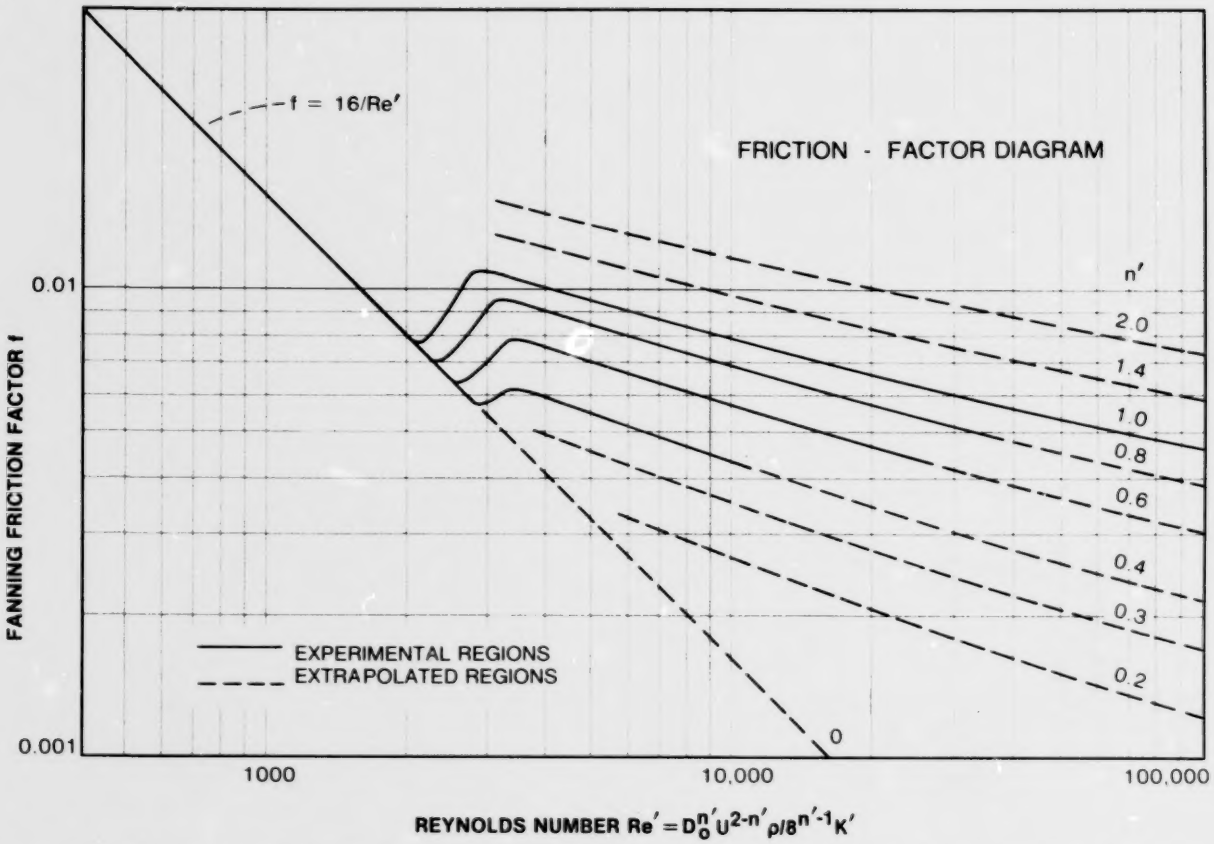

Figure 7-2. Friction factors for flow of purely viscous fluids in pipes. (by permission, from D.W. Dodge and A.B. Metzner, A.I.Ch.E.J., 5: 189, 1959.)

weight transmitted to the pipe wall. This produces segregated or sliding bed flow.

If the effective viscosity of the slurry is the same as that of the carrier fluid (perhaps as a result of particle migration away from the pipe wall), the friction factor for the slurry flow in Equation 7.5 is the same as that for the fluid. At a given velocity, this means that in turbulent flow the head loss is proportional to the density of the slurry. A dimensionless excess head loss ϕ is defined by

$$\phi = (i - i_f)/C_{vd}\, i_f \qquad ...7.8$$

where C_{vd} is the volume fraction of solids in the delivered mixture. For this particular case of pseudohomogeneous turbulent flow, head losses may be estimated from the expression:

$$\phi = (s - 1) \qquad ...7.9$$

If the effective viscosity is higher than that of the fluid, ϕ values in turbulent pseudohomogeneous flow are correspondingly increased above the value given by Equation 7.9.

For a pseudohomogeneous laminar flow, i is independent of slurry density and depends on the effective viscosity of the mixture (as well as V and D). This means that for pseudohomogeneous laminar flow ϕ should also be independent of V. Therefore, the best evidence of true pseudohomogeneous flow is a set of velocity-independent ϕ values obtained in an experimental test conducted in either laminar or turbulent flow.

A reasonable estimate of the laminar-turbulent transition condition can be obtained from the criterion Re=2100, using the effective viscosity of the slurry deduced from the head losses.

7.4 Segregated Flow

This third limiting case has been given a variety of names, including "stratified" and "sliding-bed" flow. The descriptive term "heterogeneous" has also been employed, although this should probably be used to describe any non-homogeneous (or non-pseudohomogeneous) flow. That is, the heterogeneous classification should include actual flows of a non-homogeneous type as well as the third limiting case. In this sense, heterogeneity for a flow reflects its non-axisymetric character.

The name proposed here for the third limiting case is "segregated" flow. It differs from the so-called sliding bed flow in that it includes flows with beds which are sheared internally as well as those sliding en bloc. No matter what the nature of the stress transfer within the mixture, the boundary friction between the particles and the pipe wall is known to depend on the total immersed particle weight as described in Reference 2. For this third limiting case, frictional head losses can also be predicted theoretically.

The best analysis of segregated flow is that of Wilson (Refs. 2 and 3) and the value of the model is not only its predictive capacity for head losses. Because it is based on a more thorough analysis, it contributes to understanding of the flow and of phenomena such as deposition.

Although Wilson's derivations permit the model to be presented elegantly as a graphical relationship between dimensionless groups, the simpler approach employed here is suited for computer programming.

The model employs mass balance and force balance relationships for the flow depicted schematically in Figure 7-3. The hypothetical horizontal interface separates the particle-free upper layer from the lower layer of concentration C_2. Neglecting the difference between particle and fluid velocities in the lower layer, the mass balances are, for fluid and solids respectively:

$$(1-C_v)\,AV = A_1V_1 + (1-C_2)\,A_2V_2 \qquad ...7.10$$

$$C_vAV = C_2A_2V_2 \qquad ...7.11$$

Force balances can be written for each layer and these are coupled through the stress on the interface. Assuming the upper layer velocity V_1 is greater than V_2, the force balances are, for steady flow

$$i\,\rho_l\,g = (\tau_1S_1 + \tau_{12}S_{12})/A_1 \qquad ...7.12$$

$$i\,\rho_l\,g = (\tau_2S_2 - \tau_{12}S_{12})/A_2 \qquad ...7.13$$

Stress τ_1 is calculated from an expression of the form of Equation 7.5:

$$\tau_1 = f_1V_1^2\rho_l/2 \qquad ...7.14$$

The friction factor f_1 can be calculated from $(DV\rho_l/\mu_l)$ using Figure 7.4. Stress τ_{12} depends on the difference in velocity between the layers and the particle diameter:

$$\tau_{12} = f_{12}\,(V_1-V_2)^2\,\rho_l/2 \qquad ...7.15$$

where, according to Wilson, f_{12} is given by the rough boundary relationship as

$$f_{12} = 2/[3.36 + 4\log(D/d)]^2 \qquad ...7.16$$

Stress τ_2 includes two effects: particle-wall sliding friction and fluid-wall friction in the lower layer. Neglecting any

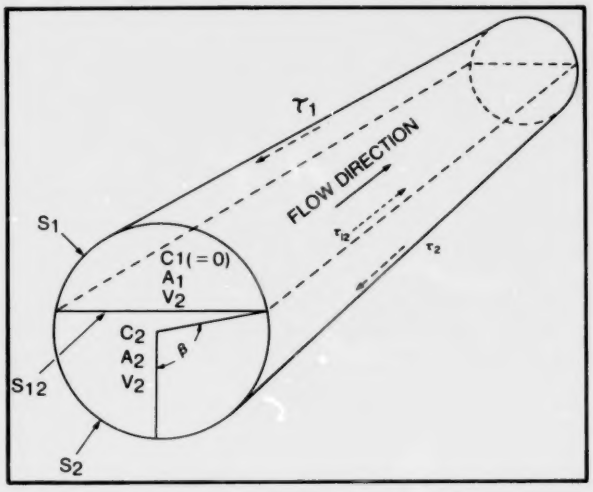

Figure 7-3. Cross-section of pipe for segregated flow model.

transmission of stress τ_{12} through the lower layer, the expression for τ_2S_2 (in terms of the subtended angle β) is

$$\tau_2S_2 = f_2V_2^2\rho_l S_2/2 + 0.5\,(\rho_s-\rho_l)g\,D^2(\sin\beta - \beta\cos\beta)\eta_sC_2 \qquad ...7.17$$

Friction factor f_2 can be approximated as f_1. The second term on the right hand side of Equation 7.17 was derived by Wilson on the assumption that all the immersed weight of the particles is transmitted to the pipe wall. The coefficient of kinematic friction η_s between the particles and the pipe wall is a new variable, whose omission from earlier models is obviously a limitation of these. A difference in η_s is probably the major reason for differences in head loss reported recently for steel and plastic pipes.

In a design situation V, C_v, C_2, d, η_s, ρ_l, μ_l and D are known and this means that f_1 and f_{12} are known. S_1, S_2 and S_{12} are simple functions of D and β so that unknown quantities are i, V_1, V_2 and β. When the equations are solved simultaneously, the values of these four quantities are obtained. The example in Appendix 7-3 shows an iterative method which converges rapidly.

In summary, three idealized cases can be analyzed theoretically; homogeneous flow, pseudohomogeneous flow and segregated flow. The vast majority of practical flow situations occur somewhere between these cases. Such flows are heterogeneous and, although predictive methods have been proposed, all are empirical in some essential sense. For both deposit velocities and head loss predictions, experimental characterization is desirable unless substantial safety margins in design can be tolerated.

7.5 HETEROGENEOUS FLOWS

Most of the experimental studies in the literature have been concerned with these flows. Both deposit velocities and head losses are of interest.

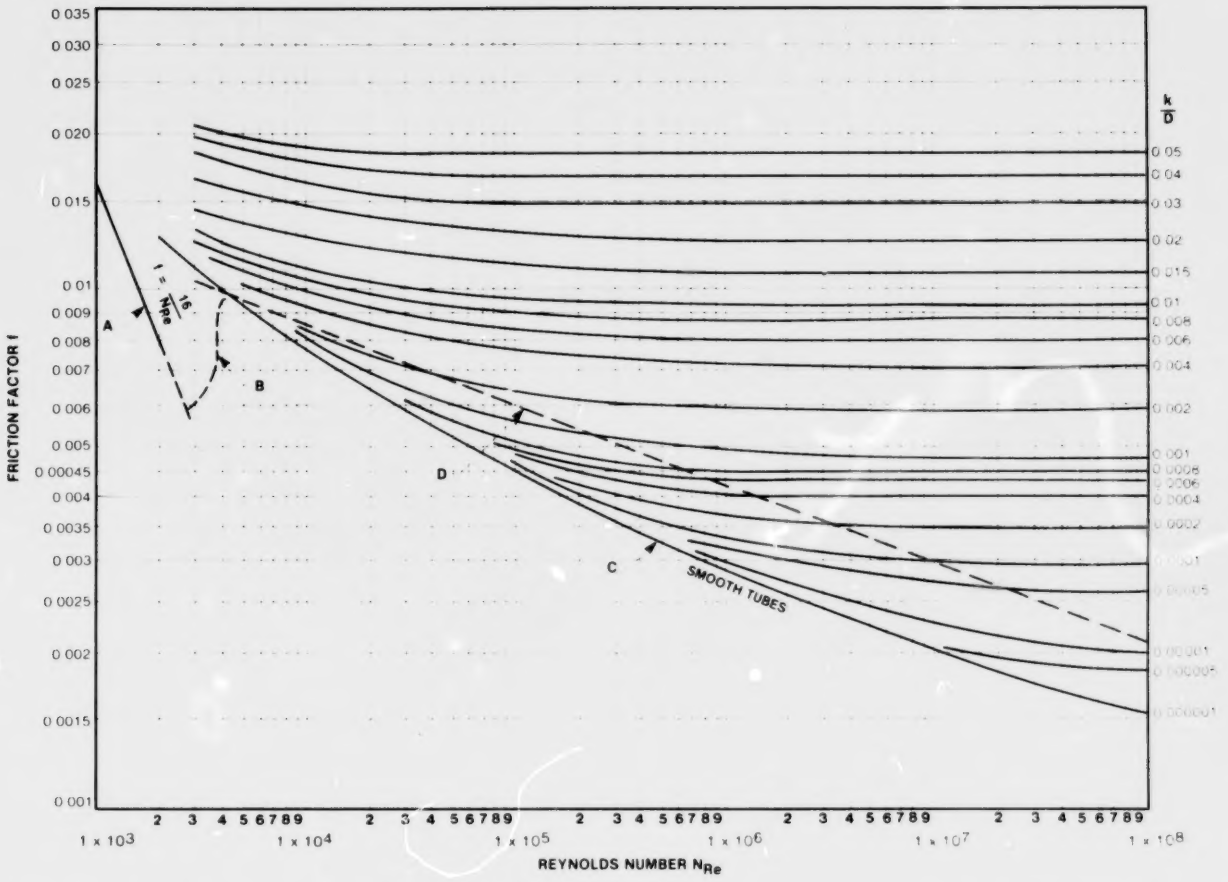

Figure 7-4. Fanning friction factors. Reynolds number $N_{Re} = DV\rho/\mu$, where D = pipe diameter, V = velocity, ρ = fluid density, and μ = fluid viscosity. [by permission, based *on Moody*, Trans. Am. Soc. Mech. Eng., *66, 671 (1944)*.]

7.5.1 Deposit Velocities

These are of great importance in the design of slurry pipelines since it is rarely desirable to operate with a partially blocked pipeline. Head losses would be increased by the reduced cross-sectional area and the erodible upper surface introduces a complication when the conditions of flow vary. In fact, once a deposit forms, fluctuating flow conditions may eventually lead to blockage.

With a stationary deposit present, the flow obviously cannot be considered homogeneous or pseudohomogeneous. These are limiting cases and deposition occurs only in slurries with some heterogeneous character. Of course, deposition can occur with fully segregated flows and in fact these are the only ones for which a theoretical treatment of deposition has been possible.

Few flows are likely to fall within this limiting condition, however, so that correlations which summarize the empirical evidence still have to be used for predictions in the transition region. There are numerous limiting velocity equations; in 1974 Carleton and Cheng (Ref. 4) listed over 60. Because these equations rely on experimental data, the wisest choice is always to use the latest one with the largest base of reliable data. Data reliability (or comparability) is a serious problem since prolonged visual observation may be required to detect deposition in laboratory studies. This is necessary because, at velocities just above deposition, slowly moving dunes (within which the particles are stationary for periods of a minute or more) travel along the bottom of the pipe. Other sources of difficulty with the data base for empirical correlations are:

a) few data are available for slurries with mean particle diameters greater than one mm,
b) few data are available for viscosities lower than one centipoise,
c) the effect of fines (acting perhaps as viscosity-increasing agents) can be substantial but has not been investigated systematically,
d) the effect of slurry concentration is different for fine particles than for coarse ones (perhaps this is also a viscosity effect).

A conservative (upper limit) estimate of deposition velocity is given by the nomogram of Wilson and Wood in Figure 7-5. This nomogram applies for viscosities near

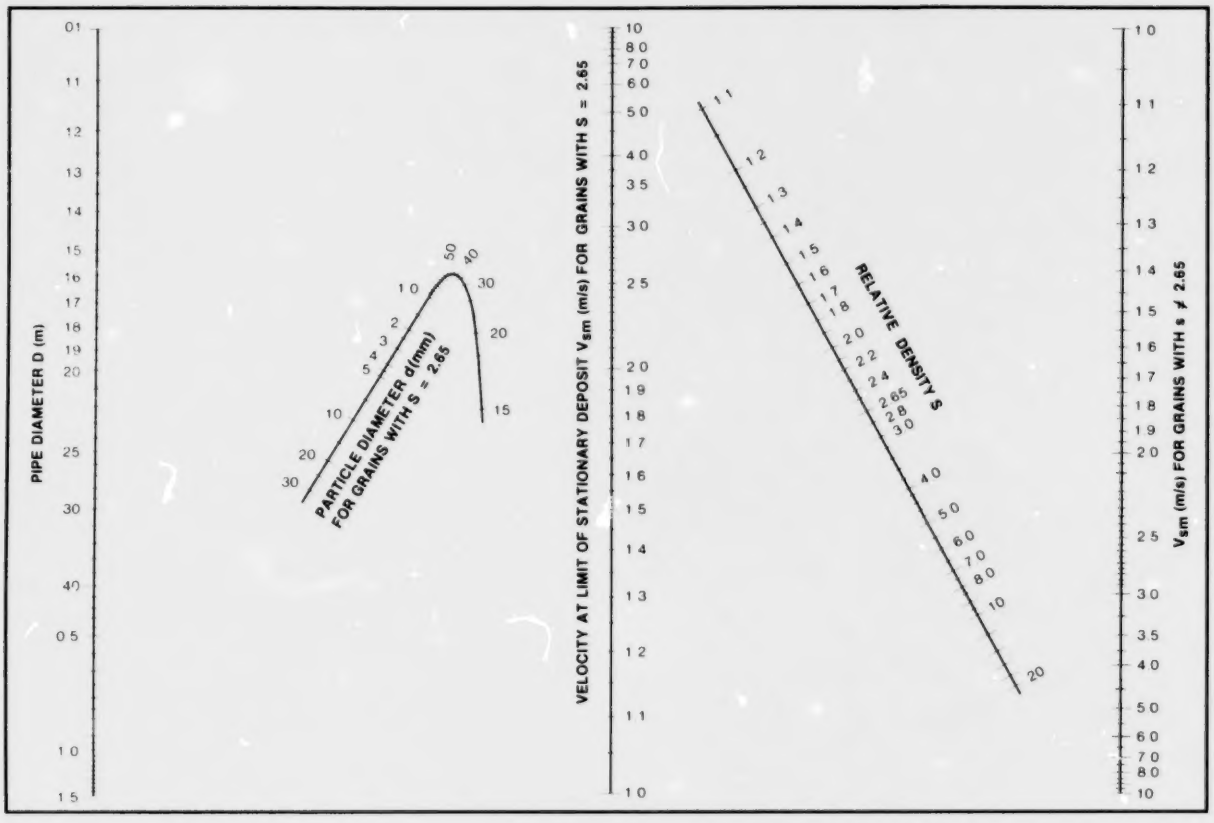
PIPE DIAMETER D (m)
PARTICLE DIAMETER d(mm) FOR GRAINS WITH S = 2.65
VELOCITY AT LIMIT OF STATIONARY DEPOSIT Vsm (m/s) FOR GRAINS WITH S = 2.65
RELATIVE DENSITY S
Vsm (m/s) FOR GRAINS WITH s ≠ 2.65

Figure 7-5. Generalized nomographic chart for maximum velocity at limit of stationary deposit. (by permission, from K.C. Wilson, Paper A1 pp 1-12, 6th Int. Conf. Hyd. Transport of Solids in Pipes. BHRA, 1979.

one centipoise and its use is explained in Reference 4. It should be used with due regard to the difficulties listed above. Any lack of precision in use of the nomogram is less than that in the prediction itself.

The nomogram indicates that a maximum deposit velocity occurs near a particle diameter of 0.5 mm. There is some evidence to support this. However with coarse particles, slowly moving dunes form just above the deposition velocity and are probably just as undesirable as stationary beds. This means that an additional safety allowance is desirable when the nomogram is used for particles larger than 0.5 mm. A correlation, also limited by the factors stated above, is that of Oroskar and Turian in Ref. 5. The correlation uses a hindered settling velocity, estimated from

$$V_t' = V_t (1-C_v)^2$$

in

$$V_c/[gd(s-1)]^{0.5} = \alpha_1 C_v^{\alpha 2}(1-C_v)^{\alpha 3}(D/d)^{\alpha 4}\, Re_p^{\alpha 5} X^{\alpha 6} \qquad ...7.18$$

where:

α_1 = 1.85; α_4 = 0.378;
α_2 = 0.1536; α_5 = 0.09;
α_3 = 0.3564; α_6 = 0.30

and

$$Re_p = D\rho_f\, gd\, (s-1)^{0.5}/\mu_f$$

$$X = 2/(\pi)^{0.5}[(2/(\pi)^{0.5})\gamma \exp(-4\gamma^2/\pi) + \int_{\gamma}^{\infty} \exp(-4\gamma^2/\pi)d\gamma]$$

and

$$\gamma = V_t'/V_c$$

A sample calculation is shown in Appendix 7-4.

The effect of particle size and concentration on deposition velocity has been discussed by Parzonka, Kenchington and Charles (Ref. 6).

Although the nomogram and the correlations are useful for purposes of estimation, for major projects it

would be necessary to measure the deposition velocity in a test program using pipes as close to full scale as possible. In so doing, the margin of overdesign can be reduced because size distribution effects often produce lower deposition velocities in large pipes than are predicted from the correlations.

7.5.2 Head Losses

Considerable progress has been made in this field in the last thirty years, as the result of attempts to develop predictive theoretical models. These theoretical studies have been stimulated by industrial-scale experiments, documented sufficiently to permit analytical modelling. As these experimental and theoretical studies continue, further progress can be anticipated. It is important to recognize that a considerable fraction of this development has occurred in Canada and the role of funding by the Federal Government has been of paramount importance in this research.

As understanding of the subject has evolved, the relationships used for prediction have increased in complexity. In the age of the digital computer, this complexity is of little practical disadvantage. This trend is likely to continue.

The first comprehensive empirical correlation was that of Durand and Condolios (1951) which, in principle, excluded only homogeneous flows. In terms of ϕ and the drag coefficient C_D for a particle settling in the carrier fluid, their relationship (as modified by Worster to include the effect of particle density) is

$$\phi = 81[gD(s\text{-}1)/\ V^2(C_D)^{0.5}]^{3/2} \qquad ...7.19$$

For particles with a broad size distribution there is no truly satisfactory mean drag coefficient, but the inverse summation of Equation 7.20 is better than using the median (d_{50}) particle size:

$$1/(C_{Dm})^{0.5} = \Sigma x_i/(C_{Di})^{0.5} \qquad ...7.20$$

where x_i is the fraction of particles in screen interval i with mean diameter d_i.

Drag coefficients are correlated with particle and fluid properties through the Archimedes number $4d^3(\rho_s\text{-}\rho_f)g\rho_f/3\mu_f^2$. For non-spherical particles, measurements are required. For sand and gravels the coefficients in the correlations of the form

$$C_D = a\ Ar^b$$

are given approximately by the following table.

Range	a	b
$Ar < 24$	576	-1
$24 < Ar < 2760$	80.9	-0.475
$2760 < Ar < 46100$	8.61	-0.193
$46100 < Ar$	1.09	0

These values may be used as approximations for particles similar in shape to sand.

One of the first mechanistic equations was derived for the segregated flow condition (Newitt et al., Ref. 7) which was described as "sliding bed" or "flow with saltation" in the original reference. The expression

$$i = i_f + 0.8\ C_{vd}(s\text{-}1) \qquad ...7.21$$

may be written as

$$\phi = (0.4\ f)[gD(s\text{-}1)\ V^2] \qquad ...7.22$$

Comparing Equations 7.22 and 7.19, the principal difference lies in the exponent of 3/2, compared to unity. For the coarse particles likely to produce segregated flows, C_D is nearly constant. This fact, and the fact that Equation 7.19 obviously cannot apply to pseudo-homogeneous flows, suggests that the Durand-Condolios correlation was strongly influenced by heterogeneous flow results.

Since near-pseudohomogeneous flows are of great practical importance, Charles' equation (1970) represented a significant advance:

$$\phi = (s\text{-}1) + K[gD(s\text{-}1)\ V^2(C_D)^{0.5}]^{3/2} \qquad ...7.23$$

where K is a coefficient. Although the effective viscosity of the slurry would tend to increase the importance of the first term, an equation of this type (with the (s-1) multiplier, K and the exponent regarded as correlating parameters) can be fitted to virtually all test data. It is clearly superior to correlations which use piecewise fits to a relationship between ϕ and $[gD(s\text{-}1)\ V^2(C_D)^{0.5}]$. Equation 7.23 also influenced the next series of predictive relationships, which may be classified as multiple-equation models.

It has long been the practice in river engineering to divide the total solids content into two fractions: "suspended load" particles supported by fluid lift forces, and "bed load" particles whose immersed weight is transmitted to the wall. The suspended load particles contribute the so-called "homogeneous" (actually pseudo-homogeneous) component. If there were no viscosity correction, its contribution to ϕ would be given by Equation 7.9.

The bed load particles contribute the so-called "heterogeneous" component so that the final relationship, neglecting the possibility of turbulence suppression in the pseudohomogeneous component, is

$$\phi = (s\text{-}1)(v_{susp}/v_f)^m(C_{susp}/C_v) + 81[1 - (C_{susp}/C_v)][gD(s\text{-}1)/V^2\Sigma x_i/(C_{Di})^{0.5}]^{1.5}_{bedload} \qquad ...7.24$$

The exponent m has a value of 0.15. To separate the total solids content into suspended and bed load fractions,

Wasp et al. (Ref. 8) used a heuristically justified expression based upon the ratio

$$(V_s\ (igD\ 4)^{0.5}\ \text{or}\ (V_s\ V^*)$$

A simple alternative method for estimating C_{susp} has been suggested by Professor R.R. Faddick of the Colorado School of Mines. If one assumes that the "suspended load" particles would settle in the carrier fluid with a particle Reynolds number $(d\rho_l V_s\ \mu_l)<1$, Equation 7.24 can be used. In terms of the drag coefficient

$$C_D = 3\ V_s^2\ 4gd\ (s-1) \qquad ...7.25$$

the criterion is equivalent to $C_D > 24$. A slurry viscosity must be measured or estimated if this method is used.

Other two-equation models have been proposed, all of them incorporating the bed load and suspended load separation of the mixture in some manner. Recently, Clift et al. (Ref. 9) proposed a method of correlating experimental measurements (for a slurry of given concentration)

$$\phi = A'(s-1)\ (C_{susp}\ C_v) + B\ (1 - C_{susp}\ C_v)\ [gD(s-1)\ V^2] \qquad ...7.26$$

If A' approaches 1, this indicates an effective viscosity close to that of the carrier fluid. To predict the suspended load fraction, the expression they suggest is

$$(C_{susp}\ C_v) = \Sigma\ 0.6\ (V_t\ V_*)^2 \exp(45\ d_s\ D) \qquad ...7.27$$

However this relationship is not completely satisfactory. From the standpoint of simplicity and theoretical justification, Equation 7.26 has much in common with Equation 7.24.

For near-segregated flows, a modified version of the two layer model can be derived. If C_1 is the suspended load concentration, assumed constant within the pipe, the mass balances for fluid and solids are modified from Equations 7.10 and 7.11:

$$(1-C_v)AV = (1-C_1)A_1V_1 + (1-C_2)\ A_2V_2 \qquad ...7.28$$

$$C_vAV = C_1A_1V_1 + C_2A_2V_2 \qquad ...7.29$$

The force balances in Equations 7.12 and 7.13 are unaltered but density ρ_1 replaces ρ_l in Equation 7.14 and 7.15 where

$$\rho_1 = \rho_l[1 + C_1(s-1)]$$

Because of the increased buoyancy produced by the suspended load particles, the expression for τ_2S_2 is altered to:

$$\tau_2S_2 = f_2V_2^2\ \rho_1S_2/2 + 0.5(\rho_s-\rho_l)gD^2(\sin\beta - \beta\cos\beta)\ \eta_vC_2' \qquad ...7.30$$

where:

$$C_2' = C_2(1-C_2-C_1)\ (1-C_2)$$

An expression for C_1 is required to complete the model. Equation 7.27 represented an attempt to deal with this problem and in fact no definitive expression has been produced to date. A possible expression in terms of the mean in-situ concentration C_v

$$C_vA = C_1A_1 + C_2A_2 \qquad ...7.31$$

is

$$C_1\ C_v = \text{function}(d\ D),\ Ar,\ (s-1),\ V^2\ gd \qquad ...7.32$$

Research in progress should allow this functional relationship to be determined. Reference 10 gives a complete description of this model.

7.6 SUMMARY

In summary, the preferred methods for head loss calculations are:

a) homogeneous flows - Equations 7.2 or 7.6 (laminar) and Figures 7-1, 7-2, and 7-4 (laminar or turbulent),
b) pseudohomogeneous flows - Equation 7.9,
c) segregated flows - Equations 7.10 to 7.17,
d) heterogeneous flows - Equation 7.24 or the model in Reference 10.

Experimental measurements can be correlated with Equations 7.23 or 7.26. However, scale-up will be conservative in both cases.

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APPENDIX 7-1 HEAD LOSSES - HOMOGENEOUS FLOW

Estimate the pressure drop for a Bingham fluid with the following properties:

ρ = 1200 kg/m^3
μ_p = 0.028 Pa•s
τ_y = 1.4 Pa

Find i at V = 1 m/s if D = 0.050 m and 0.200 m.

a) D = 0.050 m

$He = \rho D^2 \tau_y / \mu_p^2 = 5357$

$Re = DV\rho / \mu_p = 2143$

Figure 7-1 shows this flow is laminar. In this case one should use Equation 7.2. However, iteration is required to find τ_o, which gives i from Equation 7.3. To begin the iteration, neglect the term $(\tau_y / \tau_o)^{4/3}$.

$\tau_o = 4\tau_y/3 + \mu_p (8V/D)$
$= 6.34$ Pa

From this estimate one can see that the neglected term is in fact very small (7.9×10^{-4}) compared to unity.

Thus $i = 4\tau_o / \rho_l g D$
$= 0.0518$ mH_2O/m pipe (ans)

b) D = 0.200 $He = \rho D^2 \tau_y / \mu_p^2 = 85714$

Re = 8572

Figure 7-1 suggests this flow is turbulent with f (smooth pipes) of 0.0069. Using equation 7.5:

$\tau_o = 4.14$ Pa

$i = 8.44 \times 10^{-3}$ mH_2O/m pipe (ans)

For rough pipes or where conditions justify conservative design, the friction factor should be taken from Figure 7-5.

APPENDIX 7-2 HEAD LOSSES - PSEUDOHOMOGENEOUS FLOW

Estimate the pseudohomogeneous pressure drop for the slurry specified below:

Particle density: 1420 kg/m^3

In-situ mean concentration = 0.40 (volume fraction)

D = 0.159 m

V = 4.0 m/s

Fluid: water at 20°C

Pipe roughness is 4.6×10^{-5} m.

To find i_f, calculate f

$Re_f = DV\rho_f / \mu_f = 6.36 \times 10^5$

$\epsilon / D = 2.9 \times 10^{-4}$ so f = 0.0039 (from Figure 7-5)

$i_f = 0.080$ m/m

$i = i_f [1 + C_v (s-1)] = 0.0934$ m/m (ans)

APPENDIX 7-3 HEAD LOSSES - SEGREGATED FLOW

Find i at V = 1 m/s for the slurry described below if D = 0.154 m, and the roughness is 4.6×10^{-6} m.

d = 0.031 m

C_v = 0.40

η_s = 0.50

C_2 = 0.52

ρ_s = 1400 kg/m^3

ρ_f = 1000 kg/m^3

μ_f = 0.001 Pa•s

To solve: Assume β = 1.4 radians to start the iterations.

From the mass balances, Equations 7.10 and 7.11, one finds

V_1 = 0.38 m/s

V_2 = 1.96 m/s

These velocities are obviously wrong. Before altering β, one first calculates i from Equation 7.12 and 7.13. Using these values, one finds

$i = 0.09$ (Eq. 7.12)

$i = 0.015$ (Eq. 7.13)

β is increased and the calculations are repeated until the values agree. At convergence

$\beta = 2.196$ radians

$V_1 = 1.54$ m/s

$V_2 = 0.905$ m/s

$i = 0.208$ (Eq. 7.12)

$i = 0.210$ (Eq. 7.13) (ans)

APPENDIX 7-4 DEPOSIT VELOCITIES

For a sand of density 2650 kg/m^3 and median particle diameter of 0.5 mm, find the deposit velocity in a pipe with D = 0.32 m if the carrier fluid is water at 20 °C. Take C_v as 0.15 and assume the drag coefficient C_D is related to the Archimedes number $Ar = 4\ d^3\rho_f g(\rho_s-\rho_f)/3\mu_f^2$ by the expression $C_D = 79.55/Ar^{0.452}$

a) From Figure 7-4, V_c is estimated as 3.9 m/s. (ans)

b) Using the correlation of Oroskar and Turian:

V_t is calculated from the Archimedes number

$Ar = 4\ d^3\ \rho_f\ (\rho_s-\rho_f)\ g\ /\ 3\ \mu_f^2$

$= 2685$

$C_D = 2.24$

$V_t = (4\ gd\ (s-1)\ /\ 3\ C_D)^{0.5}$

$= 0.069$ m/s

so $V_t' = 0.05$ m/s and $X \rightarrow 1.0$

also $Re_p = 28773$

and substituting in Equation 7.18

$V_c/(gd(s-1))^{0.5} = 37.8$

so that $V_c = 3.4$ m/s (ans)

APPENDIX 7-5 HEAD LOSSES - HETEROGENEOUS SLURRIES

(Use of a Modified Form of the Durand Equation)

Calculate i for the coal slurry shown below at a velocity of 2.8 m/s in a pipeline of 0.159 m I.D. The temperature is 19°C, the fluid density and viscosity are 999 kg/m^3 and 1.02 cp.

Concentration: 32% by volume

Solids Density: 1380 kg/m^3

The size distribution is given in the form of a screen analysis:

Screen Opening, mm	Percent finer
12.7	100.0
6.35	98.6
2.38	75.5
0.84	36.3
0.42	26.0
0.21	18.5
0.074	13.5

Because no viscosity data are available, the slurry viscosity is assumed to be related to the suspended load concentration by the expression

$$\mu_m = \mu_f\ [\exp(2.5\ C - 2C/0.65)]/(1 - C/0.65)^2$$

where C is the volume concentration of suspended load particles (C_{susp}).

Determine C_{susp} using Faddick's suggestion. The effective diameter in each screen interval is calculated from the geometric mean of the limiting screen openings. For the smallest fraction the effective diameter is taken as 27.2 microns.

Drag coefficients are computed from Archimedes number. The relationship, shown below, is reasonably satisfactory for Canadian coals (Ref. 11).

$Ar < 24$: $C_D = 576/Ar$

$24 < Ar < 4660$: $C_D = 128/Ar^{0.482}$

$4660 < Ar$: $C_D = 2.89/Ar^{0.0344}$

d_i, mm	C_{Di}
9	1.75
3.9	1.90
1.4	2.10
0.59	4.6
0.30	12.5
0.12	62.5
0.027	5990

Plotting C_{Di} vs d_i, and selecting the cutoff point at $C_{Di} = 24$, gives a separation into suspended load and bed load

particles at d = 0.2 mm. From the total size distribution one concludes that C_{susp}/C_v is approximately 0.185: the two finest fractions contribute the suspended load. This allows one to calculate the viscosity and density of the suspended load mixture.

$$\rho_m = 999\,(1-0.059) + 1380\,(0.059)$$

$$= 1021 \text{ kg/m}^3$$

$$\mu_m = 1.02\,[\exp\,[(2.5)(0.059)-2(0.059)^2\,0.65]]\,[1-(0.059/0.65)]^{-2}$$

$$= 1.16 \text{ cp}$$

The ratio (ν_m/ν_l) is (1.16)(999)/(1.02)(1021) or 1.11. The first term on the right hand side of Equation 7.24 is evaluated as

$$[(1380/1021)-1]\,(1.11)^{0.15}\,(0.185) = 0.066$$

To calculate the second term one needs the values of x_i for the bed load material - that which was coarser than 0.21 mm.

d, mm	$[x_i]_{bed}$	$[x_i/(C_D^{1/n})]_{bed}$
9	0.014/(1-.185) = 0.02	0.015
3.9	.231/.815 = .28	.203
1.4	.392/.815 = .48	.331
0.59	.103/.815 = .13	.061
0.30	.075/.815 = .09	.025
		Σ0.635

The second term is

$$81(0.815)^2\,[(9.8)(0.159)\,[(1380/1021)-1]\,(2.8)^2/(0.635)]^{1.5} = 2.44$$

Thus $\phi = 0.066 + 2.44 = 2.5$ according to this method of estimation. To determine i_l, the Reynolds number is evaluated using the properties of the fluid.

$$Re = 0.159\,(2.8)\,(999)/1.02 \times 10^{-3} = 4.36 \times 10^5$$

From Figure 7.5, f is 0.0034 in a smooth pipe and

$$i_l = 2(.0034)(2.8)^2/9.8(0.159) = 0.0342 \text{ m } H_2O/\text{m pipe}$$

Thus

$$i = 0.0342\,[1 + 0.32\,(2.5)]$$

$$= 0.0616 \text{ m } H_2O/\text{m pipe.}$$

8. SLURRY PIPELINE DESIGN

by

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8.1 INTRODUCTION

As the words "slurry pipeline" can mean different things to different people, it may be difficult to cover all aspects of design for all types of slurry pipeline systems. In this chapter an attempt is made to be as general as possible and then use three case studies to highlight the methodology used for these distinctly different applications.

The three case studies presented in Appendices 8-1, 8-2 and 8-3 of this chapter cover the following:

a. short, small diameter pipeline to transport mine tailings to a disposal site,
b. long distance pipeline transporting coal slurry,
c. short pipeline moving coarse solids.

Like the designer for an oil pipeline, the designer of a slurry pipeline will generally start with a limited amount of information and is expected to produce a conceptual or preliminary design to generate sufficient data for a budget estimate of capital investment and operating costs. Whereas the designer of an oil line will have reasonably accurate data on the product to be moved, such as density and viscosity, and can assume the fluid to be Newtonian, the slurry pipeline designer will generally not have that much information.

Currently, if a person were required to start a preliminary design for a slurry system and had only the quantity and some basic data on the solids, the best approach would be to try and find laboratory test or operating data of systems using similar materials to arrive at approximate figures for pressure drop, pipe diameter and flow velocity. Should such data not be available, it would be difficult to come up with reasonable figures.

For a detailed design it is important to perform laboratory tests to establish the actual slurry characteristics to be used for the pipeline under consideration.

8.2 ROUTE SELECTION

Route selection for a slurry pipeline does not differ significantly from the work for any liquid pipeline system as described in Chapter 3, but there are some differences. The major difference is the requirement that slopes be kept below a maximum gradient. The designers of the Black Mesa pipeline used a maximum gradient of 16%. Other designers advocate slopes between 10% and 15%. No doubt the density and concentration of the materials shipped have a significant input in the selection of maximum allowable slope. The requirement to limit the gradient could cause the routing engineer some headaches where it comes to routing a line through a deep river valley or mountainous terrain. Another difference, at least for lines utilizing aqueous slurries, is that they could be considered to be non-hazardous to the environment.

8.3 HYDRAULIC DESIGN

The hydraulic design of slurry pipeline systems differs from the design of oil or other "single phase" liquid pipelines. Where in the latter case the designer designs a transportation system to move given quantities of liquids with known properties, this is not the case with slurry transportation. In the case of slurry pipeline design the density and bulk modulus of the solids will generally be known but not the particle size, size distribution and volume concentration, all of which affect the hydraulic characteristics of the slurry mixture. With the exception of lines used for transportation of materials with defined characteristics, such as tailings, the particle size, size distribution and volume concentration of solids become another set of variables to be considered in the system design.

Unless hydraulic data for a slurry are available from an operating system or laboratory tests done previously for similar materials, it is difficult to predict the hydraulic performance of the slurried materials without detailed laboratory testing.

The difficulty in many cases is that a designer will be required to provide a preliminary design, before any tests can be performed, to provide reasonable data for a feasibility study. In this case the designer has very few options; he can try to find data on slurry behavior for similar materials, or try to approximate the data by using one of the methods indicated in Chapter 7 to arrive at an effective viscosity or head loss figure for the specified operating conditions.

When a potential pipeline progresses from "pipe

dream" to proposal to a viable project, actual slurry properties will have to be established by laboratory testing. The laboratory work will provide the designer with data for the actual solids concentration or a number of practical concentration values. Where the particle sizes are not defined, optimum particle sizes and likely size distribution for the materials under consideration will have been considered.

As described in Chapter 7, mixtures of solids and liquids can be homogeneous, pseudohomogeneous or heterogeneous, each requiring a different approach when calculating hydraulic performance in pipelines.

In the case studies given in Appendices 8-1, 8-2 and 8-3, three different types of systems are considered to illustrate to the reader how these cases can be treated:

a. Case 1, a short mine tailings line moving a slurry with a known volume concentration and particle size which behaves as a homogeneous slurry. This slurry is a Bingham plastic slurry and has a known yield stress.
b. Case 2, a long distance coal slurry pipeline. The case starts with a preliminary design made using assumed slurry properties. Then the case is supplemented with laboratory test data to complete the designs, including the location and conceptual design of the pump stations. The slurry in this system behaves as a pseudohomogeneous mixture, where the water carrier fluid with the fine particles forms a homogeneous mixture and the larger particles provide the heterogeneous effect.
c. Case 3, a short, coarse solids pipeline, transporting coal with particle sizes up to 50 mm at relatively high velocities. The particle sizes are given and the designer has to optimize the solids/water ratio, establish the velocity, line size and pumping requirements.

8.3.1 Slurry Velocity

Velocity of flow in a slurry pipeline is more critical than for single phase liquid pipelines. If the velocity is too low, solids could settle out and start forming a bed on the bottom of the pipe. On the other hand, if the velocity is too high the solids could erode the inside of the pipe at unacceptable rates of wear. Higher velocities, of course, will also increase the friction losses and the pumping power requirements. One of the first criteria a designer has to establish is the critical flow velocity. For homogeneous flow this is the transition velocity V_T and for heterogeneous mixtures the deposition velocity V_c (Ref. 1).

8.3.1.1 Homogeneous and Pseudohomogeneous Slurries. For fully homogeneous mixtures the flow can be laminar or turbulent, as the mixture will not segregate under any circumstance. Pseudohomogeneous mixtures should be pumped at velocities which cause turbulent flow, to ensure that the solids stay in suspension and the pseudohomogeneous character is maintained. As described in Chapter 7, a reasonable estimate of the laminar-turbulent transition condition can be obtained from the criterion Re = 2100, using the effective viscosity of the slurry. Table 8.1 gives a comparison of Reynolds numbers for different pipe diameters at a constant velocity of 1.5 m/sec and indicates that for a relatively small line (for commercial purposes) of 250 mm, Re = 7500 for an effective viscosity of the fluid of 50 cSt. Based on the above, it would appear that, for homogeneous and pseudohomogeneous slurries, the transition velocity would generally be below most practical pumping velocities.

TABLE 8.1
Re at Velocity of 1.5 m/sec and Viscosity of 50 cSt (50 mm²/sec)

Pipe Size NPS	Approximate Internal Diam. (m)	Re
2	.05	1 500
4	.1	3 000
10	.25	7 500
18	.44	13 200
20	.49	14 700
24	.59	17 700
30	.74	22 200

8.3.1.2 Segregated Flow, or Flow of Heterogeneous Mixtures. Because of the non-homogeneous character of the mixture, there are more solids in the bottom half of the pipe. Careful consideration should be given to whether or not there should be a moving or stationary bed on the bottom of the pipe. As it does not appear to be economic to operate with a partially blocked line, segregated flow should be kept in a condition where all solids are moving. It is therefore advisable to operate lines moving heterogeneous mixtures at velocities in excess of the deposit velocity to ensure that all solids are in suspension. To estimate the deposit velocity for preliminary line sizing, Figure 7.5 may be used.

After laboratory testing, when all the properties of the mixture are defined, the final design can take place such that the system will transport the maximum concentration of solids at the optimum combination of line size and flow velocity.

8.3.2 Slurry Properties

Slurry properties which are of importance to the pipeline designer are; density, viscosity, heat capacity, thermal conductivity, whether the mixture is homogeneous or not, and whether the mixture has a Newtonian or non-Newtonian rheology.

Most of the slurry characteristics are dependent on one or more of the following; properties of the solids, properties of the carrier fluid, solids concentration and particle size and shape.

Depending on the type of pipeline under consideration, some of the slurry properties can be varied and in other cases they may be fixed.

Abrasiveness of the slurry may not be of primary consideration when computing the hydraulic performance of a pipeline but it strongly influences operating and maintenance aspects of the line.

8.3.2.1 Density. The density of a slurry mixture (ρ_m) depends on the density of the solids (ρ_s), the density of the carrier fluid (ρ_l) and the solids concentration. Solids concentration may be expressed as volume fraction C_v or weight fraction C_w. While it is more convenient to use the weight fraction C_w for throughput calculations, it is the volume fraction figure C_v which influences the hydraulic characteristics of the mixture.

Whereas $$C_w = \frac{\text{Weight of solids}}{\text{Weight of mixture}}$$

it can be shown that:

$$C_w = \frac{C_v \rho_s}{\rho_m}, \qquad \ldots 8.1$$

and that $$C_v = \frac{C_w \rho_m}{\rho_s} \qquad \ldots 8.2$$

Substitution of $\rho_m = C_v \rho_s + (1-C_v)\rho_l$ in Equation 8.1 results in

$$C_w = \frac{C_v \rho_s}{C_v \rho_s + (1 - C_v)\rho_l} \qquad \ldots 8.3$$

which gives a relationship between C_w and C_v when the densities of the solids and liquids are given. Using the following formula

$$\rho_m = \frac{1}{C_w \rho_s + (1 - C_w)\rho_l} \qquad \ldots 8.4$$

to determine the density of the mixture when C_w, ρ_s and ρ_l are given, and substituting in Equation 8.2, the value for C_v can be computed.

8.3.2.2 Viscosity. While the term viscosity in reality is only correct for Newtonian fluids, it is a useful expression which can be used for slurry hydraulic computations. The expression "apparent viscosity" is used in this chapter to indicate that the values given only apply at the conditions of flow indicated.

It seems quite natural that, when solids are added to a liquid, the mixture gets thicker and thus the viscosity increases as the solids content is increased. It also appears reasonable that the mixture viscosity depends upon the size of the particles and the distribution of particle sizes.

Several researchers have attempted to predict the viscosity of mixtures of solids and liquids and Thomas (Ref. 2) has found that the formula

$$\mu_m / \mu_o = 1 + 2.5\, C_v + 10.05\, C_v^2 + 0.00273 \exp(16.6\, C_v) \qquad \ldots 8.5$$

where: μ_m = viscosity of the mixture,
μ_o = viscosity of the liquid,
C_v = solids concentration by volume,

gives reasonable results for values of C_v up to 0.40. However, the problem is that this correlation is valid only for spherical particles of uniform size, a condition seldom encountered by the designer of a commercial slurry pipeline.

As it is essential to have accurate values for the apparent viscosity of the slurries to be transported at the operating conditions (temperature, concentration and flow velocity), it is almost always mandatory to perform laboratory tests to obtain these figures.

This requirement leaves the designer, who has to come up with a preliminary design and cost estimate prior to any laboratory testing, in the unfortunate position that he is working with a largely unknown quantity. In order to arrive at a suitable line size and friction losses, a viscosity figure or a friction factor is required.

For preliminary design purposes it may be possible to use operating data from existing slurry systems or laboratory test data for similar materials, and even Equation 8.5 could be used to establish a minimum value for the apparent viscosity. Operating data indicates that actual viscosities of mixtures of irregular shaped particles can be more than double the values arrived at with Equation 8.5.

Table 8.2 gives a comparison of friction factors and apparent viscosities at different flow velocities for a coal slurry in turbulent flow. These results and tests performed with other slurries indicate that the apparent viscosity increases as the flow velocity decreases. This trend occurs for both pseudohomogeneous and partially segregated flows.

Figure 8.1 gives a graphic representation of the results of flow tests performed on slurry samples of the same Alberta coal as in Table 8.2. Plotting the apparent viscosities computed from the observed flowrates and headloss figures on a logarithmic scale produces nearly straight lines for the portions representing turbulent flow velocities. Where the flow velocities approach the critical flow range, the apparent viscosities increase disproportionally. This effect is due to segregation and the sliding bed type of flow. For homogeneous slurries the apparent viscosities are much less influenced by a change in flow velocity.

On the high velocity end of the scale the curves begin to approach the viscosity of water as the flow becomes pseudohomogeneous.

The curves shown in Figure 8.1 are for slurries of the same coal at different volume concentrations but there was some variation in the particle size distribution, which

TABLE 8.2
Test Run of Judy Creek Coal in Water

Coal Density	1460 kg m^3
Water Density	1000 kg m^3 @ 8°C
Mixture Density	1161 kg m^3
C_v = 0.35	C_w = 0.44

Particle Size Distribution

Sieve Opening (mm)	Wt. % Passing
0.044	11.5
0.074	13.4
0.105	15.7
0.149	19.3
0.210	24.4
0.297	31.3
0.420	40.9
0.595	51.3
0.841	64.9
1.190	81.8
2.380	99.5

Test Run Data in 107.6 mm ID Pipe

V m/sec	Δh m(water)/m	Friction Factor Fanning	Apparent Viscosity mm^2/sec	Reynolds Number Re
3.05	0.0803	0.0036	2.19	150 062
2.74	0.0731	0.0044	3.57	82 518
2.44	0.0699	0.0053	7.44	35 309
2.13	0.0649	0.0065	14.56	17 747
1.83	0.0559	0.0078	22.2	8 858
1.65	0.0544	0.0091	37.1	4 784

may account for the difference in slope of the lines. The mixtures used for curves 1 and 3, although not identical, were very much alike, as were the mixtures which produced curves 2 and 4, the latter having a somewhat higher content of finer particles.

The flow regimes covered in these tests varied with velocity and a comprehensive interpretation would be difficult. However, as long as the pipe size in the test is close to that to be used, the test results may be interpreted in the form of apparent viscosities. (Refer to discussion in section 7.2.)

Supplying a pipeline designer with a set of similar curves indicating the apparent viscosities at different solids concentrations, from tests run in a pipe with a size as close as practical to the line size or sizes under consideration, would enable him to closely estimate the pressure drop.

8.3.2.3 Particle Size and Particle Size Distribution. Slurry properties depend to a large extent upon the size of the particles and the distribution of different sizes of particles throughout the mixture. The viscosity of the mixture and the degree of homogeneity is directly affected by the size of the particles and the distribution. Larger particles tend to increase the deposit velocity and cause the mixture to be heterogeneous but do not increase

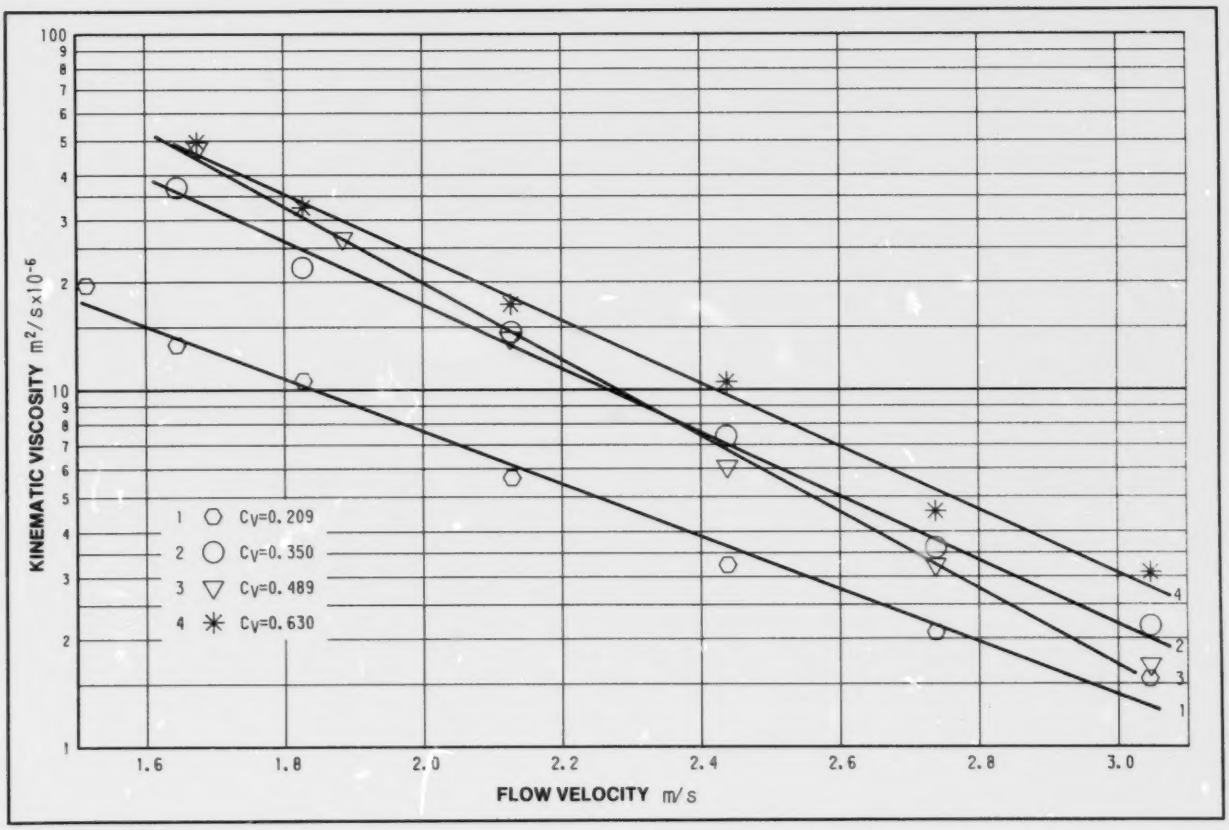

Figure 8.1 Apparent viscosities of coal slurries at different velocity & volume concentrations

viscosity. A mixture with smaller particles would have a lower deposit velocity, would be more likely to behave like a homogeneous mixture but have a higher apparent viscosity. As it has a lower deposit velocity it could be pumped at a lower velocity, resulting in lower pressure drops and energy requirements to transport the same volume of solids.

A mixture containing a variety of particle sizes could have the advantage of being able to transport the larger particles at a lower velocity due to the fact that the carrier fluid and "fines" component of the solids would form a homogeneous carrier fluid with higher density which carries the larger particles at lower velocities.

8.3.2.4 Slurry Concentration. As indicated in Figure 8.1 and Section 8.3.2.2, the viscosity of a slurry mixture increases with the concentration of solids in the mixture. As the viscosity is also dependent upon the particle size, shape and particle distribution, it is difficult to look at the solids concentration in isolation. However, it can be clearly shown that in all cases higher concentrations mean higher apparent viscosities. There is a clear economic incentive to try to transport as high a solids content as practical in the smallest amount of carrier fluid, but the mixture has to be pumpable. Thus there is an upper limit to the practical value of apparent viscosities.

For mixtures where the particle sizes are given, laboratory tests can determine what the practical limits of solids concentration are. Too low a concentration would require an excessive amount of carrier liquid; too high a concentration would cause high viscosities, and hence excessive pumping power requirements.

As indicated above, the solids concentration can be given as a volume fraction or a weight fraction. The volume fraction C_v is a more practical limit for comparing hydraulic performance because it is the volume concentration which affects the viscosity. The concentration fraction by weight given as C_w is more practical when considering quanitities of solids to be carried, usually given in tonnes per day or per year.

8.3.2.5 Specific Heat and Thermal Conductivity. The heat capacity and thermal conductivity of a slurry mixture may or may not be of importance to the pipeline designer. Considering that most of Canada is subject to severe winter temperatures, a review of the thermal characteristics of a proposed line, however short it may be, may not be out of order. For a long distance slurry line where considerable amounts of friction heat could be generated, the hydraulic computations should include the effect of heat generation and dissipation. For oil pipelines heat dissipation is generally not a problem for lines of size 30 (762 mm) and smaller, and there should be no reason why this should be much different for slurry pipelines.

8.3.3 Pressure Drop Calculations

The method of calculating pressure drop for a slurry pipeline varies with the type of system and materials to be transported. For a short line, either in-plant or solids disposal where the power cost is a small part of the overall system operating cost, the pressure drop could be estimated on the high side and the emphasis on the pumping system would be to ensure that the solids keep moving. For a long distance commodity pipeline where the power cost is one of the main operating cost items, it is essential that the pressure drop is calculated accurately so that the overall system can be designed for efficient operation.

8.3.3.1 Homogenous and Pseudohomogeneous Mixtures. For a line moving a slurry which is a homogeneous mixture or which behaves as a pseudohomogeneous mixture, pressure drop calculations would follow the method outlined in Chapter 3. Unless a value for the apparent viscosity of the fluid mixture is available, it is difficult to accurately calculate the pressure drop. If the pumping velocity is such that the flow regime would be turbulent, the friction factor and hence pressure drop is not very sensitive to changes in Reynolds number.

Example: A pipeline is required to move a slurry with density of 1150 kg/m^3 and unknown viscosity at a rate of 20,000 m^3/day. The internal diameter of the line is 432 mm. If the viscosity of the material is estimated at 100 centistokes ±50%, the resulting pressure drop would be 114 kPa/km + 13%/-18%.

The method to be used to calculate the pressure drop for a pipeline intended to transport a slurry which is expected to be a homogeneous or pseudohomogeneous mixture would generally follow the outline given in Chapter 3. The difficult part would be to arrive at values to be used for the apparent viscosity of the fluid mixture at the operating velocities of the proposed pipeline.

It can be seen in Figure 8.1 that the apparent viscosity can vary significantly with the flow velocity, as well as with the solids concentration, for the slurry examples used in those tests. It is therefore essential that sufficient laboratory test data are available to a designer before accurate pressure drop calculations can be performed.

As the majority of pipelines operate in the turbulent flow regime where the friction factor and hence pressure drop is not very sensitive to variations in Reynolds number (inversely proportional to viscosity), a reasonable estimate of the apparent viscosity will result in a reasonable pressure drop value for the purpose of a preliminary design or feasibility study.

Example: Assume a pipeline is required to move a slurry with the properties given in Table 8.2. Line size is NPS 16 (406 mm). Compute the pressure drop curve at flow velocities between 1.6 and 3.0 m/sec and compare results for an assumed kinematic viscosity of 10 cSt and for the viscosities given in curve 1 in Figure 8.1. The resulting curves are given in Figure 8.2.

With reference to Figure 8.2, if it is assumed that the line is 50 km long and needs to operate at 2.5 m/sec to achieve a throughput of 26 200 m^3/day, the preliminary

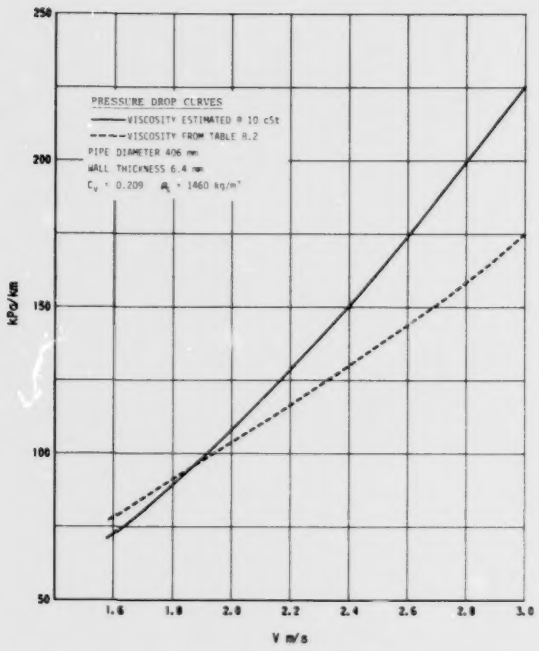

Figure 8.2 Pipeline pressure drop curves

estimate would be based on an operating pressure drop of 8150 kPa (using 10 cSt).

Using the test data and computing the apparent viscosities at the corresponding flow velocities, a designer would obtain an operating pressure drop of 6850 kPa. If the estimate were to be based on the higher pressure drop, the figures for installed pumping power and energy consumption would have been approximately 19% too high. The pipe cost would also have been too high, as pipe with thinner wall could be used.

In reality the pipeline designer would also evaluate other possibilities by repeating the computations for slurries with higher volume concentrations of solids. Very likely the final design would result in a smaller diameter pipe or a much reduced pumping velocity, or both, and a slurry mixture with higher solids concentration.

The computations above also indicate that the selected line size would be small for the design throughput because, at a flow velocity of 2.5 m/sec, the pumping pressure required would be excessive. For the short line under consideration the 6850 kPa operating pressure could be accepted, but if the line length were 200 or 400km an inappropriate number of pumping stations or a higher operating pressure would be required. A more reasonable selection would be one or two pipe sizes larger with correspondingly lower operating velocities and pressures.

8.3.3.2 Heterogeneous Flow. Calculating the pressure drop for flowing heterogeneous mixtures becomes more complicated. For preliminary design purposes it may be possible to use the same approach as for pseudohomogeneous mixtures, if the heterogeneous effect is small. For true heterogeneous flow or segregated flow as described in Chapter 7, Section 7.5, it becomes more complicated. The example given in Appendix 7-3 gives a method for headloss calculations using the two layer method whereby the solids content is divided into two fractions, "suspended load" particles supported by the fluid lift forces and "bed load" particles whose immersed weight is transmitted to the pipewall.

8.3.3.3 Coarse Particle Solids. The flow of coarse particle solids in a liquid medium is not really a form of slurry transportation but more of a flushing action sometimes referred to as hydrotransport. A method for calculating pressure drops for this type of transport is given in Reference 3 which claims to have had reasonable success with mine coal occasionally containing as much as 35% refuse. The size of the coal was -10 cm at C_v of 25%.

The formula used is a correlation by Worster and Denny (Ref. 4).

$$\frac{i_m - i_w}{C_v i_w} = 120 \left[\frac{V_m^2}{gD(s-1)} \right]^{-1.5} \qquad ...8.6$$

which can be written as:

$$i_m = i_w \left[1 + 120\, C_v \left[\frac{V_m^2}{gD(s-1)} \right]^{-1.5} \right] \qquad ...8.7$$

and gives the pressure drop for the mixture as a function of the pressure drop for water. This equation corresponds to Equation 7.19 with a particle drag coefficient of 0.59. In these equations

i_m = hydraulic gradient of mixture (m water m),
i_w = hydraulic gradient of water (m water m),
C_v = concentration fraction of solids by volume,
V_m = mean mixture velocity in m sec,
g = gravity constant 9.8146 m sec^2,
D = pipe internal diameter in m,
s = relative density of the solids.

8.3.3.4 Flow Enhancing Additives. Since the start of the successful operation of the Black Mesa pipeline, researchers in several countries have been working on methods to improve the hydraulic characteristics of slurried materials.

Whereas the Black Mesa line transports a coal slurry with a solids concentration of between 45 and 50% by weight and particle sizes of up to 2.5 mm, attempts are being made to increase the solids concentration and particle size and still have a pumpable mixture.

The technique of using chemical additives to reduce the apparent viscosity of slurry mixtures has been used extensively for the composition of drilling muds in the oil and gas drilling industry.

Research is being conducted in several areas and some of these efforts are showing promising results. The potential slurry pipeline designer is well advised to keep informed about additives.

Substantial research has been undertaken on the possible improvement of coal slurry pipeline technology. The potential volumes of coal to be shipped are large and water supply very often is a sensitive issue, so naturally a method to increase the solids concentration and thus reduce the water requirements would be beneficial.

Research is being conducted on: the possiblity of "designing" stable homogeneous mixtures which would not settle in storage tanks or when the pipeline is shut down; mixtures which can be burned "as is" without dewatering; and the use of additives to create a heavier carrier fluid which would keep larger particles in suspension and could be pumped at lower velocities.

The effect of such additives must be tested in pipelines since the role of slurry viscosity on pipeline head losses and deposit velocities is a complex one.

Although at the time of writing no operating system appears to be using the techniques mentioned, some of which are subject to proprietary rights, it is an area which should be watched closely.

8.4 MECHANICAL DESIGN

Mechanical design for slurry pipelines is very similar to that for other liquid pipelines as outlined in Chapter 3, Section 3.4. Normal pipeline design is mainly concerned with strength of materials, stresses caused by operating conditions, seismic conditions, soil movement and vibration. For slurry lines, the same conditions have to be considered with the addition of allowances for erosion or corrosion-erosion.

Selection of valves for liquid pipelines is generally a matter of individual preference as much as price. Valves to be used in a slurry pipeline would have to be selected on the basis of suitability for use with the particular solids and fluid present, which may severely limit the options. The presence of H_2S in the fluid would require special valve trim which most manufacturers would supply as an option.

8.4.1 Operating Pressures

The process of determining a practical operating pressure for a slurry pipeline generally follows the same reasoning used for conventional liquid pipelines. As outlined in Chapter 3, after the total pumping pressure necessary to move the required volumes through the system has been calculated, the designer has to select practical maximum operating pressures while considering codes and equipment specifications. For example, the pressure ratings given for flanges and valves in Table 8.3 indicate that a 1440 psi maximum operating pressure will require ANSI 600 class valves.

Pipeline operating pressures are generally selected in the range of 4970 to 9930 kPa. Pressures below these figures are not practical for several reasons, and the matter is discussed further in Section 8.4. Operating pressures above 9900 kPa are not commonly used for larger diameter pipelines, as the pipe wall thickness required would increase the pipe cost greatly and flanges and valves in the larger diameter sizes are not readily available.

TABLE 8.3
Pressure Ratings

Nominal Pressure Class (PN)	MOP kPa	ANSI Class Rating	MOP (psi)
20	2240	150	325
50	4970	300	720
68	7450	400	1080
100	9930	600	1440
150	14900	900	2160

Having established the total system pressure drop required, the designer has to decide how many pump stations to use and how to divide the required pumping power. Generally, the cost of installing pumps, once the size of the units has been established, does not vary much on the basis of dollars per installed horsepower. The incremental cost of installing the required number of pumps in two or three locations instead of all in one place is relatively small.

The cost of electric energy when purchased in sufficiently large quantities is also relatively constant so the operating expenses do not vary greatly.

The pipeline cost, however, is greatly influenced by pump station spacing as the cost of pipe is fairly constant expressed in dollars per unit weight. Using two pump stations instead of one reduces the MOP required by 50% and hence the pipe cost by 50%. For example, the pipe cost for a 500 km NPS 20 line operating at 8800 kPa would be in the range of $90 million. By doubling the number of pump stations from three to six and operating the system at 4400 kPa, the pipe cost would be reduced by approximately $45 million. The cost of acquiring three extra station sites and incremental facilities could add $3 million to $6 million to the pump station cost.

8.4.2 Selection of Pipe Grade and Wall Thickness

As currently there is no CSA code for slurry pipelines, any line to be designed should follow the requirements of CSA Z183. The CSA has instituted a slurry pipeline code subcommittee which in due time will provide a new code, or supplement to CSA Standard Z183, applicable to slurry pipelines. The ultimate design criteria for slurry pipelines are likely to be somewhat different than those given in CSA Z183.

Equation 3.25, as given in Chapter 3, will be valid

$$t = \frac{P\,D\,10^{-3}}{2\,S\,F\,E}$$

but the design factor F could be different from the values given in CSA Standard Z183. This is similar to the draft

ASME Code B31.11 which allows a design factor of 0.80 instead of the 0.72 used in ANSI B31.4 and CSA Z183.

In addition to the wall thickness calculated by using Equation 3.25, an allowance has to be made for erosion or corrosion-erosion where such is anticipated. As the rate of wear caused by erosion depends on several factors such as velocity of flow and abrasiveness of mixture, it will be difficult to predict unless operating data or laboratory test data for similar conditions are available.

8.4.3 Pipeline Equipment

Pipeline equipment such as pumps,valves and end closures for scraper traps and other fittings in many cases will be designed for other liquid based pipelines and used where conditions are appropriate. In other cases, equipment will have to be designed specially or adapted to suit the conditons for the more stringent requirements. As the design of slurry pumps is covered in Chapter 6, this section will address the requirements for valves and other fittings. It is difficult to be specific as the requirements may vary widely from application to application. Main features to be considered in the design of equipment for slurry systems are resistance to abrasive wear and the elimination of cavities in valves which could fill up with solids and cause jamming and scoring of seals during operation.

8.4.4 Corrosion and Erosion Protection

In a recent study by the Alberta Energy Resources Conservation Board (Ref.5) it was found that approximately two-thirds of all reported pipeline leaks were caused by corrosion. The study further indicated that the majority of the leaks, approximately 65%, expressed in number of leaks per 1000 km of operating pipelines, occurred in water and multiphase pipelines. Of the leaks caused by corrosion, approximately two-thirds were due to internal corrosion and only one-third due to external corrosion.

The evidence given in the above reference indicates that it is very important that the design of slurry pipeline systems incorporates protection and/or mitigating measures against corrosion.

8.4.4.1 Internal Corrosion and Erosion. Without going into the mechanism of corrosion, it should be obvious that a pipeline moving abrasive solids in a water based slurry combines the two factors causing material loss from the inside of the pipe wall. The water provides the electrolyte necessary for corrosion and the solids will provide the abrasive wear which keeps the metal surface bare and thus accelerates the electrolytic corrosion process. Researchers have found (Ref. 6) that in some cases the material loss from corrosion exceeds the abrasive losses.

One can see from existing operating pipelines that pipelines can be operated successfully with acceptable rates of pipe and equipment wear. Whereas it is difficult to be specific when adressing the broad spectrum of slurry pipeline technology, some of the more obvious remedies can be indicated and others referred to in a general sense. Where the slurry to be transported is of a nature which enhances corrosion, corrosion prevention measures should be considered. Anti-corrosion additives can successfully reduce internal corrosion. The selection of materials and quantities should be determined by experiment or based on prior use by others. As erosion is caused by the abrasive action of the solids on the internal surfaces of the pipe and fittings, reducing the velocities of the solids would reduce the erosion rate. It is believed that, at flow velocities under 2 m/sec, erosion is not generally a problem. Where coarse materials have to be transported at the high velocities required to keep them in suspension, it may be necessary to increase the pipe wall thickness to allow for wear over the project life. On the other hand, a coal slurry line transporting fine slurry of non-abrasive nature may require no special measures, as there will be no erosion and the corrosion rate will be reduced by oxide or scale coatings on the inside of the pipe.

8.4.4.2 Internally Lined Pipe. The use of resilient or erosion resistant linings inside the pipe may solve the corrosion/erosion problem for some applications but may not be very practical for others. The problem with applying internal coatings is that joints have to be coated after the pipes have been welded together, which may be difficult if not impossible to do for smaller diameter pipes. A large, approximately one metre diameter, water pipeline which was internally coated with an epoxy material and installed in 1982, had the field joints coated manually by people travelling inside the pipe on powered trolleys. As the problem of pipe wear due to coarse solids moving at high flow velocities is generally associated with relatively short segments of pipeline, it may be practical to use precoated sections of pipe which would be joined mechanically. As the technology of coating pipe is continually improving, a system designer should attempt to use the most up-to-date solution available for the particular application under consideration.

8.4.4.3 Non-metallic Pipe. The use of PVC, polyethylene and other man-made materials for pipe has been limited to low pressure applications until recently. Current catalogs for reinforced resin pipe indicate that such pipe is available for operating pressures of 4100 kPa (600 psi) in nominal sizes up to 600 mm (20 in), which should for some cases provide a viable alternative to lined steel pipe. Tests for erosion resistance are advisable, however.

8.4.4.4 External Corrosion Prevention. The technology of preventing external corrosion of pipelines is well established and consists of one or more of the following methods: application of an external coating to the pipe, installation of impressed current cathodic protection and the use of sacrificial anodes. Currently,

there are a number of pipe coatings available, some of which are applied in the field as the pipeline is installed and others which are applied under more controlled circumstances in a coating yard or at the pipe mill before the pipe arrives in the field. All pipe coatings have one thing in common. They are not perfect and by the time the pipe is installed and buried they will have some flaws or pinholes in them. To prevent the corrosive action from attacking the pipe at these imperfections, an impressed current cathodic protection system is used. The impressed current system ensures that the pipe to soil potential is kept sufficient to counteract any galvanic action which may be present and which could cause pipe corrosion. Most pipeline operating companies monitor the output voltage and current of their cathodic protection installations, as any change could indicate damage to pipe coating and hence increased corrosion risk. Sacrificial anodes are basically performing the same function as the impressed current systems but generally are used for short sections of pipe, or to assist where a local condition is not adequately covered by the main system. The industry standard for corrosion control is outlined in the Canadian Gas Association corrosion practice (Ref. 8).

8.5 PUMP STATION DESIGN

Design of pumping stations for slurry pipelines generally follows the same reasoning as for other pump stations. However, due to different requirements, the end result may be quite different and may vary considerably for different slurry pipeline systems.

8.5.1 Pumps and Drivers

The "workhorse" of the vast majority of cross country liquids pipelines is the centrifugal pump. Also, in the dredging industry, large diameter low rpm centrifugal pumps are commonly used to move large quantities of coarse and abrasive materials at low pressure. Current technology indicates that for all but some fine slurries of non-abrasive materials and some applications as low pressure charge pumps, centrifugal pumps are not practical and that positive displacement pumps are to be used for most high pressure slurry applications. The reader is referred to Chapter 6, "Slurry Pumps", for a more detailed discussion.

Pump drivers for slurry pipeline systems to date have been electric motors. Other pipelines have utilized diesel engines and turbines in locations where electric power was difficult or uneconomic to obtain but in these cases the pipeline carried its own fuel. As batching fuel through a slurry line does not appear very practical, electric drivers are likely to remain the common providers of motive force for slurry pipelines.

Because of the abrasive nature of most slurries,flow control valves as used on other liquid pipelines are not practical for slurry systems. It is thus essential that speed control of the pumps be incorporated in the drive system. Existing operating slurry pipelines have used fluid drive, eddy current and wound rotor motors and other systems for speed control of pumps, (Ref. 7). More recently, advances have been made in the development of solid state electronic frequency convertors which can be used with standard induction motors to provide a wide range of speed control. They are available for most motor sizes expected for pipeline service, do not have most of the disadvantages of the drives listed above (see Ref. 1) and can be used for positive displacement pumps as well as centrifugals.

8.5.2 Power Requirement

The power requirement for a pipeline system is a function of pumping pressure and flowrate. The following equation based on commonly used units for pipeline use, calculates the input power to the pump.

$$P = \frac{\Delta p\, Q}{864\, E} \qquad ...8.8$$

where: P = pump shaft power demand in kW,
Δp = differential pressure across the pump in kPa,
Q = throughput per pump in m^3/day,
E = pump overall efficiency in %.

For electrically powered stations the total power requirement also includes losses in the drive motors and any variable speed drive units, feeder cables and step down transformers as well as any other loads for lighting, heating and auxiliary equipment. The total station power demand can be from 10 to 20% more than the actual pumping requirements.

8.5.3 Station Equipment and Layout

Station piping for slurry pump stations requires more attention to details than for other liquid pipeline systems. Where the selection of suitable valves for liquid hydrocarbon use is almost a matter of individual preference, this is not the case for slurry systems, as discussed in Section 8.4 "Mechanical Design". Station piping also requires special attention. The designer has to design station piping such that there is sufficient fluid velocity to prevent solids from settling and also keep the velocity low enough to prevent excessive erosion. Sharp bends should be avoided where possible and where this cannot be done, they should be installed so they can be replaced quickly when required. Dead pockets which become plugged with solids also should be avoided.

Pump stations can be classified into two main categories, origin or source stations, and booster stations. At the origin station the slurries are taken from the slurry preparation plant or storage facilities and pumped to the mainline pump suction by suction boosters or charge pumps. The storage facilities may or may not be part of pump station installations. At origin stations it is advisable to have a "time delay" loop installed through which the slurry passes before it goes to the pipeline and where the slurry properties are monitored. If an "off spec" material

is received, it can be detected and diverted to a holding tank or pond before it reaches the pipeline.

Mainline booster stations for liquid hydrocarbon systems generally do not have any storage facilities, but for slurry systems it may be necessary to install tankage if the line cannot be shut down without the risk of plugging. This requirement varies with the materials to be pumped. Pump stations handling liquid hydrocarbons or slurries using hydrocarbons as carrier liquids will have to be laid out with due regard for the spacing requirements for hazardous areas of the electrical code and utilize electric equipment approved for use in appropriate area classifications. Water based or inert slurry systems do not require these precautions.

Pump stations handling aqueous slurries should be designed to ensure that equipment and piping can be kept from freezing by installation indoors and/or insulation and heat tracing and burial below the frost line for station piping. The drain piping should be laid out so that all process piping can be drained or pumped out in case of a winter emergency.

8.5.4 Special Equipment Requirements

Depending on the materials to be transported, it may be necessary to install special equipment to keep solids out of pumps or to flush out the pumps prior to shutdown and to refill them before startup.

For a pipeline handling coarse material of an abrasive nature, pump wear could be greatly reduced if only the carrier fluid passed through the pumps and the solids were introduced into the fluid later. Kamyr Inc. (Ref. 3) has developed a rotating loading device which reportedly can be used to introduce solids with particle sizes up to 100 mm into a medium pressure flowing line. A system like this could be very useful for pipelines moving coarse materials too large to pass through the pumps.

Another system, currently in use in hydraulic hoisting from underground mines, is the "lock hopper system" (Ref. 7). The lock hopper system consists of two sections of pipe where the slurry is separated from water by a sphere, not unlike a bi-directional pipe prover. While one hopper is being filled with slurry, the other one is being emptied into the pipeline at high pressure. The high pressure pumps only pump water and operate at maximum efficiency. The arrangement requires good controls, and a substantial number of motor operated valves.

Where non-homogeneous slurries are pumped, it may be necessary to install flushing systems to ensure that all solids are flushed out of a pump when it is stopped for any length of time. As the flushing medium would probably be the same as the carrier fluid, this would require a source of supply and/or storage facilities and a means of getting the material to the stations.

8.5.5 Standby Power

It is essential that each pump station is equipped with a standby generator of sufficient capacity to operate the valves and pumps necessary to flush out the mainline pumps and other equipment and to provide power for trace heating and controls in the event a power failure occurs.

8.6 INSTRUMENTATION AND CONTROL

The control system for a slurry pipeline should differ very little from other pipeline control systems. Naturally, the system for a 1000 km coal slurry line would be considerably more sophisticated than that for a 10 km mine tailings line. In this discussion the remarks will be directed generally to the more complicated systems for long distance pipelines. A system would consist of station controls and a supervisory control system.

8.6.1 Station Controls

Station controls consist of a sequencing control system which open and close valves and start or stop pumps and/or other equipment, and an instrumentation system which includes pressure, temperature and or other limit switches and process controllers which could be used to control pressures, flow rates, power demand and density of slurry.

Sequencing controls, upon receipt of command signals, start and pace through the control sequence for a particular equipment item. For instance, where the "start mainline pump" command is given, the sequencing system would open the pump suction valve, check for suction pressure, fill the pump case if it had been drained, start the drive motor and, if pump has speed control, bring pump up to main operating speed and open the discharge valve. Upon receipt of stop signal, the shutdown sequence would be initiated. The pump starter would be tripped out, the suction and discharge valves would close, if required, pump cavities would be flushed out, valve cavities would be flushed and pump unit would be ready for restart. The process control system consists of pressure, flow, density and/or power demand transmitters which feed proportional signals to the process control system or to individual process controllers. The control system compares variables with set point values and adjusts pump speed or control valve settings to make corrections if process values differ from set points.

Until a few years ago, the sequencing systems consisted of relay panels which evolved into fixed, wired static devices and later into programmable logic controllers. Similarly, process controls consisted of pneumatic or electric signal transmitters which would feed signals into individual process controllers which received analog low pressure air, millivolts or milliamps DC input signals and would transmit similar control signals to the controlled devices.

The programmable logic controllers have capability to accept analog inputs and perform the control functions which used to be done by individual controllers. As this equipment is in a state of constant evolution, more and

more options and sophistication no doubt will become available.

8.6.2 SCADA (Supervisory Controls and Data Acquisition)

As the name implies, the Scada System enables control of remote stations and the acquisition of operating data from these stations. Scada equipment has evolved rapidly in the last decades from relay based pulse code systems to computer based sophisticated systems with color CRT displays. The purpose is still the same, to enable an operator located hundreds of kilometres away from a site to monitor, start and stop equipment and to receive sufficient operational data and measurements from the remote station to do so.

The master station equipment generally consists of an operator console with one or more CRT displays, a keyboard for control and data input, a central data processor commonly backed up by a fully redundant second one, output printer(s) to log pertinent data and a non-interruptable power supply. The equipment at the remote station could be a relatively simple remote terminal (RTU) unit which responds to command or interrogation demand signals from the master station, or could be more sophisticated and be the heart of the local control system and perform the sequencing and control functions described in Section 8.6.1 above. Master station and RTU's communicate over leased telephone circuits, VHF, UHF or microwave, depending on need and availability.

The display format varies from system to system due to requirements, degree of sophistication and individual preference. Displays can be in alphanumerical form, a simple listing of the devices and a statement about their status. Displays such as "pump No. 1", "on" or a schematic diagram of the station can be displayed using color codes to indicate the equipment status.

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APPENDIX 8-1 SHORT MINE TAILINGS LINE

1. *Requirements.* The main requirement for the proposed line is to transport mine tailings from a plant site to a disposal site over a distance of 3 km. The amount of material to be disposed averages 1000 tonnes per day and the line should be designed for a peak load of 1200 tonnes per day.
2. *Pipeline Route and Environmental Studies.* The route has been selected, the line is 3.0 km in length and disposal site is 100 m lower in elevation than the plant site. Environmental work assumed to have been performed by others.
3. *Specification of Materials to be Transported.*
   - Mine tailings, - 28 mesh.
   - Carrier fluid, water.
   - Density of solids, 1420 kg/m^3.
   - Density of mixture, 1218 kg/m^3.
   - Particle size distribution, Table 8.A.1.

   Laboratory analysis indicates that the material can be pumped in high volume concentrations as a homogeneous mixture and has Bingham plastic characteristics.
4. *Approach.* Determine a practical pipe size, calculate power requirements and evaluate other line sizes to optimize the design.

   4.1 *Determine Line Size.* As laboratory tests indicate that the material can be pumped in concentrations of 52% by volume at low velocitis, the first effort would be to find a pipe size for C_v of 52% and a flow velocity of 1.5 m/sec.

   At a design rate of 1200 tonnes/day and C_v of 52%, C_w would be 60.6% (Equation 8.3).

TABLE 8.A.1
Laboratory Test Data for Mine Tailings

Density Solids	1420 kg/m^3
Density Liquid	998 kg/m^3
Density Mixture	1218 kg/m^3

Particle Size Distribution

Sieve Opening mm	Weight % Passing
0.044	39
.074	47
.149	63
.210	72
.297	80
.420	88

Hydraulic Laboratory Test Data for 51.5 mm I.D. Pipe

V m/sec	Head Loss (m water/m)	Fanning Friction Factor	Apparent Viscosity (cSt)	Reynolds Number Re
2.51	0.545	0.0179	145	894
2.26	.491	.0199	145	804
1.94	.414	.0228	142	703
1.58	.356	.0295	150	542
1.29	.315	.0392	163	408
.99	.270	.057	182	281
.65	.212	.104	217	154
.50	.177	.147	236	109
.30	.141	.325	313	49.3

Weight of mixture to be moved, 1979 tonnes/day.

Volume of mixture to be moved, 1625 m^3/day = 0.188 m^3/sec.

For V = 1.5 m/sec, ID = 0.126 m.

Nearest commercial pipe size 114.3 mm (NPS 4) or 168.3 mm (NPS 6).

Try 114.3 mm with 3.6 mm wall thickness.

For internal diameter 107.1 mm, velocity = 2.09 m/sec.

4.2 *Pressure Drop and Pumping Requirements.* From laboatory test data (Table 8.A.1), apparent viscosity is 143 cSt. The pressure drop (Equation 3.4) = 1017 kPa. The elevation difference of 100 m, provides a positive head of 100 x 9.81 x 1.218 = 1195 kPa which is more than required, thus the line does not require a pump.

APPENDIX 8-2 LONG DISTANCE COAL/WATER SLURRY PIPELINE

1. *General Requirements.* The system will be required to transport 10 million tonnes of coal from the Judy Creek area in Alberta to Lloydminster, Saskatchewan. The distance is approximately 400 km. Coal density is 1450 kg/m^3. It is assumed that for the preliminary design no hydraulic laboratory test results are available and only a preliminary route has been selected. The coal would be ground to 99% passing 8 mesh, maximum particle size 2.4 mm.
2. *Preliminary Design.*
   2.1 *Establish Line Size.* For the preliminary design, a solids concentration of C_w = 50% and flow velocity of 2.0 m/sec were used as a first trial.

   At a solids concentration by weight of 50%, 10 million tonnes of coal would require 10 million tonnes of water. Total weight 20 million tonnes per year or 54 794 tonnes per day. For a minimum availability of 90%, which is conservative, the throughout capacity of the system should be 60 882 tonnes per day.

   The density of the mixture @ C_w of 50% is 1184 kg/m^3 (Equation 8.4), the daily throughput of slurry 51 420 m^3/day at 0.595 m^3/sec. For V of 2.0 m/sec the internal pipe diameter is 0.616 m.

   The nearest standard pipe size is NPS 24 with an outside diameter of 610 mm.

   For an operating pressure of 5000 kPa and a pipe grade of 359, the minimum wall thickness would be 5.9 mm (Equation 3.25). The nearest standard wall thickness is 6.35 mm.

   2.2 *Hydraulic Computations.* As no hydraulic performance data are available, the difficulty is to estimate a reasonable figure for the apparent viscosity of the slurry. From Black Mesa published operating data a value of 14 cSt can be calculated. Alternatively Equation 8.5, which applies to spherical particles of uniform size, could be used and recognizing that the value calculated would be low, doubling it as a first attempt. Using the method above, the viscosity of the mixture is estimated at 15.0 mm^2/sec (cSt).

   The pressure drop per km can now be calculated, using Equation 3.4, as 85.1 kPa/km. For the estimated length of 400 km the total system pressure drop would be 34 030 kPa. As the difference in elevation between start and finish of the pipeline is approximately 430 m, the pumping pressure required would be 34 030 - 5 000 = 29 030 kPa. At the selected MOP of 5000 kPa, this would require 6 pumping stations with approximately 3 400 kW (4 540 Hp) per station (Equation 8.8).
3. *Detailed Design.* For the detailed design, a route reconnaissance would be performed which would take into account the criteria outlined in Section 8.2. The route description for the pipeline under consideration is given in Section 3.1 of this appendix. Laboratory tests would be performed and the hydraulic test data used for the hydraulic design calculations. The remainder of the design would then be completed in the same sequence as the preliminary design, using as much detailed information as can be made available.
   3.1 *Route Description.* The pipeline route as given in Figure 8.3 starts at a plant site selected in Section 19 63 11 W 5 adjacent to and west of

Highway 32. It traverses mostly muskeg terrain in a general easterly direction and crosses the Athabasca river at km 52.2. The Athabasca river has a wide floodplain and reasonably gentle slopes such that pipeline slope limit can be maintained easily. The route continues in an almost straight line across Highway 33 at km 74.6 and the Pembina river at km 106.5. The Pembina river has a wide floodplain and a number of meanders and gently sloping banks. Continuing eastwardly the terrain changes and the route traverses more cleared and agricultural land as it approaches the Westlock area. Highway 18 is crossed at km 117.5 and again at km 132.9. The Redwater river is crossed at km 143.0 and 170.3. Highway 28 is crossed at km 172.1 and the CN railway tracks at km 173.7 just north of the town of Redwater.

The route continues on in the same direction to a crossing site on the North Saskatchewqn River in Sections 23 and 26 TP 57 R20 W.4 at km 192.1. At the crossing site the river is straight and has a moderately sloping bank on the west side and a more gently sloping bank on the east side. The route continues through mostly agricultural lands and crosses Highway 36 at km 278.4 just north of Two Hills.

The CPR line to Lloydminster is crossed at km 303, the Vermillion river at km 355.0 and the Alberta/ Saskatchewan border is reached at km 402.2 at Highway 17 approximately 1 km south of Lloydminster. The route terminates at km 404 on a site adjacent to Husky Oil's proposed upgrader site just southeast of Lloydminster.

Note: The "real" description would describe details of river crossing locations, road and rail crossings and other areas where special caution should be exercised.

Upon completion of the final survey, the total length of the line may increase by a small amount due to minor deviations and elevation changes not identified on the maps. The total length of pipe in the ground will likely be 2 to 4 km longer.

3.2 *Laboratory Test Data.* As the preliminary estimate indicates that the proposed pipeline would be NPS 24, it is essential that laboratory test runs are performed in pipe loops with similar diameters. Some scaling of data is practical but the closer the diameters the more reliable the data will be. It is assumed that the hydraulic tests for this case were performed in a NPS 20 (510 mm) loop although in reality they were not.

A data sheet from a "typical" test run is given in Table 8.B.1. A number of tests have been performed and the apparent viscosities, calculated from the head loss figures measured, are plotted in Figure 8.4 for slurry mixtures with volume concentrations of 21%, 35% and 50%. As the area of interest generally lies between 35 and 50%, plots should be made for intermediate values; these are omitted from Figure 8.4.

TABLE 8.B.1
Laboratory Test Data Sheet

Coal density 1460 kg m^{-3}, ground to -8 mesh in water,
Pipe diameter 0.4953 m,
Water density 1000 kg m^{-3}, mixture density 1161 kg m^{-3},
Temperature 8.0°C,
C_v = 35.0%.

Particle Size Distribution

Size Opening (mm)	Wt. % Passing
0.044	11.5
0.074	13.4
0.105	15.7
0.149	19.3
0.210	24.4
0.297	31.3
0.420	40.9
0.595	51.3
0.841	64.9
1.190	81.8
1.680	95.8
2.380	99.5

Head Loss Measurements

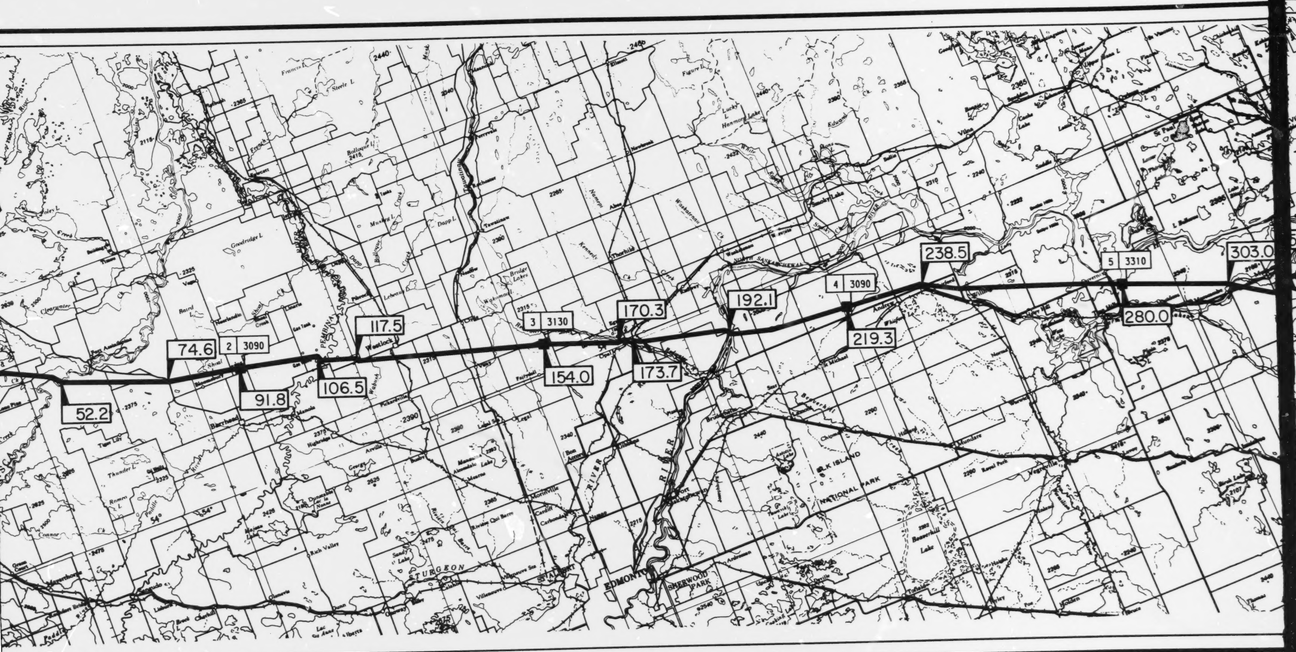
Vel (m/s)	Head Loss (m water/m)	Friction f (Fanning)	Apparent Viscosity (mm^2 sec)
3.05	0.0139	$3..10 \times 10^{-1}$	2.20
2.75	0.0126	3.47×10^{-1}	3.65
2.44	0.0116	4.06×10^{-1}	7.4
2.14	0.0104	4.77×10^{-1}	14.2
1.80	0.00871	5.63×10^{-1}	25.0
1.65	0.00819	6.29×10^{-1}	36.5
1.52	0.00760	6.88×10^{-1}	48.0
1.43	0.00710	7.27×10^{-1}	55.5

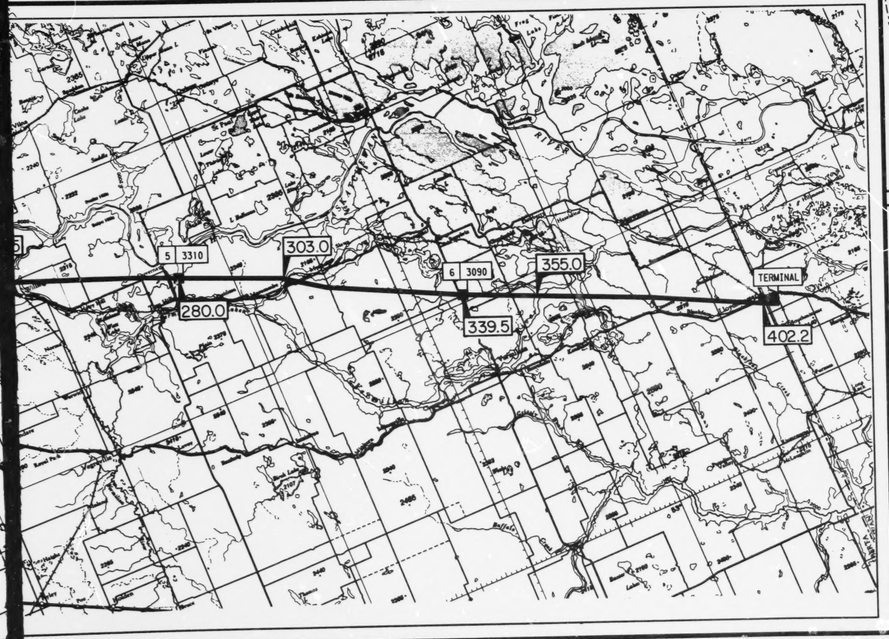
Deposit Velocity 1.3 m sec.

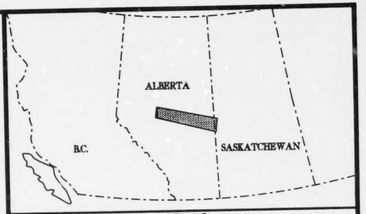
From the values in Table 8.B.2, it can be seen that the pressure drop in the pipeline can be reduced by moving the same quantity of solids in a higher concentration thus reducing the quantity of slurry to be moved. Obviously there must be a practical maximum solids concentration due to the limitation of the pumps or other reasons.

3.3 *Detailed Hydraulic Design.*
Required throughput, 10 million tonnes/year.
Coal density 1460 kg/m^3.
From preliminary design:
Daily design throughput 30,000 tonnes of coal/day, NPS 24 (610 mm) pipeline,
Average wall thickness 6.4 mm.

Perform design calculations for different volume concentrations, using apparent viscosity from Figure 8.1. The results are listed in Table 8.B.2.







INDEX MAP

LEGEND

PIPELINE

30.0 KILOMETRE POST

STATION NUMBER

1 1520 KW (HP)

PUMP STATION

10 0 10 20 MILES

10 0 10 20 30 km

Scale 1:500 000

JUDY CREEK TO LLOYDMINSTER PIPELINE

PROPOSED
PIPELINE ROUTE MAP

Monenco Engineers & Constructors Inc.

DRAWN	D.T.	DATE	85-03-28	DRAWING No.	REVISION
CHECKED	D.S.	DATE	85-03-28	FIGURE 8-3	00
APPROVED	A.H.	DATE	85-03-28	SHEET OF	

TABLE 8.B.2
Pressure Drop at Different Volume Concentrations

C_w (%)	m (kg/m³)	C_v (%)	Q (m³/day)	V (m/sec)	Viscosity (mm²/sec)	Δp /km (kPa)
44.0	1161	35.0	58 727	2.43	7.3	93.2
46.0	1170	36.9	55 741	2.30	9.8	89.8
48.0	1178	38.7	53 056	2.19	12.5	86.4
50.0	1187	40.7	50 548	2.09	16.0	83.7
52.0	1196	42.6	48 238	1.99	20.0	81.1
54.0	1205	44.6	46 104	1.91	25.5	79.4
56.0	1214	46.6	44 128	1.82	31.5	77.5*
58.0	1224	48.6	42 258	1.75	38.0	75.6
60.0	1233	50.7	40 552	1.68	43.0	72.9
62.0	1243	52.8	38 928	1.61	52.0	71.7
64.0	1253	54.9	37 410	1.55	62.0	70.5
66.0	1263	57.1	35 989	1.49	69.0	68.3
68.0	1273	59.3	34 656	1.43	80.0	67.0

As this material appears to be quite pumpable in the higher concentrations, more detailed hydraulic studies and tests should be performed to establish what maximum practical concentration can be accommodated.

The hydraulic computations should be repeated for one or more larger and smaller line sizes to provide data for optimization studies and to determine the most economical alternative.

For the purpose of this study it has been assumed that the maximum solids concentration which can be accommodated is 50% by volume and the line will be designed for C_v = 46.6%, equivalent to C_w = 56.0%.

The pressure drop computed is 77.5 kPa/km, requiring a total system pressure of 31 310 kPa. The difference in elevation of 430 m accounts for 5120 kPa, leaving a total pumping requirement of 21 190 kPa. This could be provided by three pump stations at a higher operating pressure or 6 pump stations operating at half the operating pressure.

The author favours an arrangement with the lower operating pressure using more pump stations and a lesser wall thickness in the pipeline which would be uniform throughout the system. Another school of though might consider a higher operating pressure, fewer pumping stations and a "telescoped" mainline (mainline with reduced wall thickness as the operating pressure decreases with increased distance from a pump station).

Assuming six pump stations with a maximum operating pressure of 5000 kPa, pipe grade CSA 359 (359 mPa SMY) and CSA

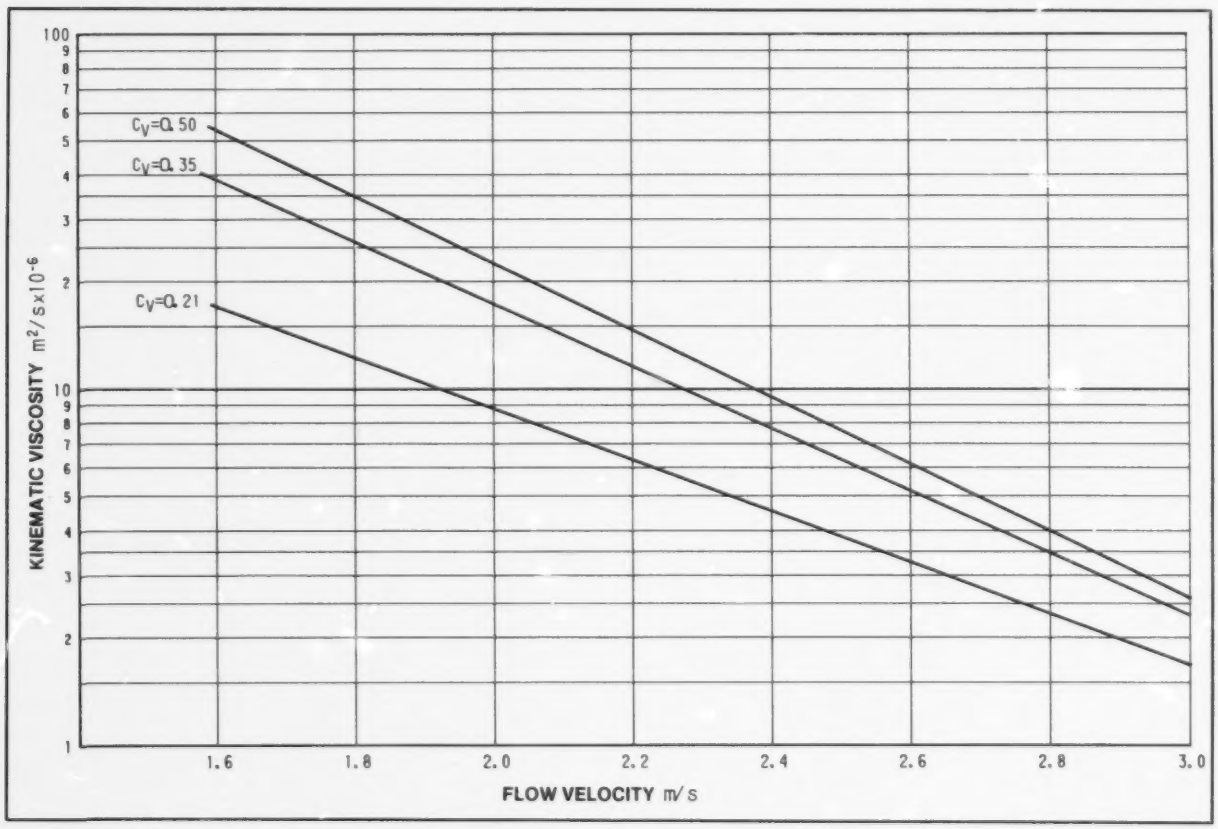


Figure 8.4 Apparent viscosities of coal/water slurry

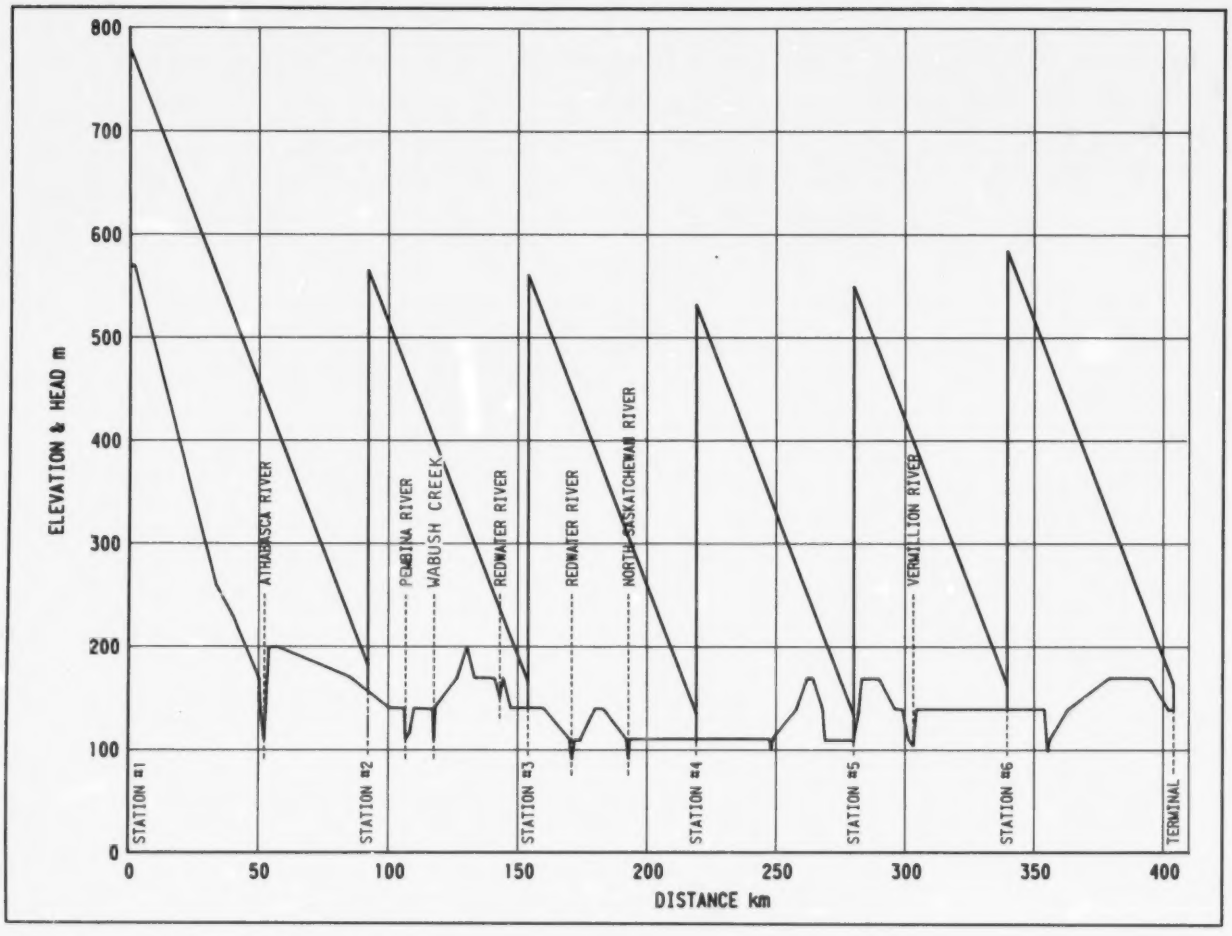


Figure 8.5 Profile & hydraulic gradient

Z.183 design criteria, the minimum pipe wall thickness would be 5.9 mm. The nearest standard wall thickness is 6.4 mm. An allowance may have to be made for abrasive wear or erosion/corrosion effect. It has been assumed that for the material under consideration, the 0.5 mm difference between standard and minimum requirement is sufficient. In reality, the abrasiveness of the material should be evaluated based on the grindability and/or wear tests done as part of the hydraulic laboratory tests. As this example deals with a long distance, long life pipeline, it is also assumed that the slurry will be treated to reduce or prevent corrosion and erosion-corrosion.

3.4 *Hydraulic Gradient and Pumping Station Location.* The pump stations will be designed for a MOP of 5000 kPa giving a slightly higher total system pressure than required and thus providing some operational flexibilty. Refer to Figure 8.5 for profile and hydraulic gradient.

Starting at the delivery point the pressure drops in the line and station locations can be computed as follows: Pump rate 44 128 m^3/day, ρ_m = 1214 kg/m^3, Δp = 77.5 kPa/km (from table in Section 3.3 above). Refer to hydraulic gradient and profile in Figure 8.5, all elevations are given in m. At 1214 kg/m^3, 5000 kPa = 420 m of slurry and the pressure drop of 77.5 kPa/km becomes 6.51 m/km. Elevations are given from reference datum of 500 m.

Starting at the terminal, elevation 140 m, adding a residual pressure requirement of the equivalent of 25 m for terminal piping losses and tank head, the total residual static head would be 165 m.

At an average station spacing of approximately 66 km, the last pump station (#6) would be located at approximately KP 338 where the elevation is 140 m.

Available pressure for the line segment equals flowing pressure plus elevation difference in metres of head and the calculation is as follows:

Discharge Pressure at Pump 6
= 420 metres of head
Elevation = 165 metres
Total = 585 metres

Residual Pressure at Terminal
= 25 metres of head
Elevation = 140 metres
Total = 165 metres

The difference 585 - 165 = 420 metres of head or 5000 kPa
Distance from station #6 = 420/6.51 = 64.5 km or at KP 339.5

Station #5, located at approximately KP 275 has an elevation of 110 m. Available pressure between stations 5 and 6 is calculated in the same manner to be (420 + 110) - (140 + 25) = 365 m.

Distance for station 5 = 365/6.51 = 56.1 which would put it at KP 283.4 where the elevation is higher. A more suitable site was chosen at KP 280 on more level ground. This requires a slightly higher discharge pressure of station #5 and possibly a short section of line with a heavier wall thickness. Discharge pressure at station #5 = 140 + 25 + (339.5 - 280) x 6.51 - 110 = 442.5 m (5 266 kPa).

Station #4, located at approximately KP 220 at elevation of 110 m. Pressure available = (420 + 110) - (110 + 25) = 395 m. 395 m/6.51 m/km = 60.7 km, locating station #4 at KP 219.3.

Station #3, located at approximately KP 160 at elevation of 140 m. Pressure available = (420 + 140) - (110 + 25) = 425 m. 425 m/6.51 m/km = 65.3 km, locating station #4 at KP 154.0.

Station #2, located at approximately KP 95 at elevation of 150 m. Pressure available = (420 + 150) - (140 + 25) = 405 m. 405 m/6.51 m/km = 62.22 km, locating station #2 at KP 91.8 where the elevation is 155 m. The station could be moved closer to the origin and operate at full MOP or be located at the selected site at KP 91.8 and operate at a discharge head of 415 m (4940 kPa).

The final step is to determine the required operating pressure at pump station #1, which is:

155 + 25 + (91.8 x 6.51) - 570 = 208 m. This requirement is rather low, but is due to the large elevation difference between station #1 and 2. The hydraulic calculations could just as well have been started from the origin and started with a "full" discharge pressure at station #1. In this case the latter alternative would have resulted in extra wall thickness requirements for a minimum of the first 50 km of line, as the hydraulic gradient has a lesser slope than the terrain.

The next step would be to evaluate the requirements for extra pipe wall thickness in the low areas as described in Chapter 3, Appendix 3-1 and Figure 3.2.

3.5 *Pumping Requirements.* The pumping power requirements are calculated for each pumping station by using Equation 8.8.

$$P = \frac{\Delta p\, Q}{864E} \text{ kw}$$

The differential pressure Δp across the pump equals the station discharge pressure minus station suction pressure plus the pressure drop in the station piping. The pressure losses in the piping are estimated at 200 kPa.

Station #1, suction pressure, provided by booster pumps = 300 kPa. Discharge pressure = 208 m or 2480 kPa. Piping losses = 200 kPa. Pump differential pressure = 2480 - 300 + 200 = 2380 kPa. For a pump overall efficiency of 80%, P = 1519 kw.

The power requirements of the other stations are calculated using the same method with the difference that the station suction pressure is provided by the upstream pump station and not by a booster pump.

The results are given in Table 8.B.3 below.

TABLE 8.B.3

Station No.	Δp in kPa	P in kw
1	2380	1520
2	4840	3090
3	4900	3130
4	4900	3090
5	5166	3310
6	4900	3090

3.6 *Selection of Pumps and Drivers.* Considering the winter temperatures in the area traversed by the pipeline, it would be most practical not to put the slurry in intermediate storage at the booster stations and to operate the system as a tight line, as is done for long distance oil pipelines. If centrifugal pumps are used, this would be the simplest solution. The apparent viscosity of the slurry is such that it could be pumped by centrifugal pumps. However, there may be other considerations (refer to Chapter

6) which make centrifugal pumps impractical. Considering the other alternative, of using positive displacement pumps, there is no problem with the pumps; but controlling the system with multiple pump stations and several pumps in parallel per station will require very close attention and a good control system.

Assuming this system will utilize positive displacement (PD) pumps, the number of pumps in each station should be selected to ensure that, if one unit failed, the remainder could keep the flow moving at a rate above the deposit velocity. In this case the nominal pumping velocity is 1.82 m/sec and the laboratory test data indicate the deposit velocity is 1.3 m/sec. By installing four parallel pumps of equal capacity, three pumps would be able to maintain a flow rate equivalent to 1.37 m/sec, which will be adequate. Each station should also include a standby pump, for a total of five pumps per station.

Variable speed control should be incorporated in at least two of the five pumps and it may be more practical to make all units identical and have all units equipped with variable speed drivers. The drivers would be electric motors, which for a coal water slurry line do not have to be explosion proof, and have a suitable frame size and rating to handle the design loads.

3.7 *Station Controls.* Each station would be equipped with the usual safety alarm and shutdown devices to protect workers, the equipment and the environment. Speed control for the units would receive inputs from suction pressure, power demand and discharge pressure sensors.

If at station #4 one of the pumps stopped, a positive pressure surge would travel upstream to station #3 and a negative surge to station #5. When the positive surge reaches station #3, the discharge pressure controller would cause the pumps (or the ones equipped with speed control) to slow down until the discharge pressure was back to normal, which would be at approximately the flow rate produced by the three remaining units on line at station #4. The process would repeat itself at stations 2 and 1. The negative surge travelling downstream would cause a low suction pressure condition at the downstream stations causing them to slow down, as well, until the whole line operates at the lower rate.

When the stopped pump at station #4 or its replacement is (re)started, the station would initially try to pump too fast and control on suction pressure. The downstream pumping stations would "see" the increased pressure and speed up again. The upstream pumps would "see" the reduced discharge pressure and also increase speed until the balance is restored.

Actually, if when the pump at station #4 stops, the system operator immediately starts the standby pump, the whole system may keep going with only the immediate upstream and downstream stations getting some of the reaction.

As a water based slurry could very well have a compressibility factor close to that of water, a surge analysis of the system should be performed to ensure that the response time of the control system can smooth out any possible "water hammer".

APPENDIX 8-3 SHORT PIPELINE MOVING COARSE PARTICLES

1. *System Requirements.* The pipeline is required to carry the output from a coal mine, located on a mountainside, to a rail loading site in the valley 650 m below at a distance of 6.5 km.

   The mine output is estimated at 6 million tonnes per year and the system availability, with allowances for weekends, holidays and system maintenance, is estimated at 75%.

   The coal has a density of 1400 kg/m^3 and the particle size is -10 cm. The average temperature of the water to be used for the hydraulic transport is 10° C.

2. *System Design.* The design daily rate based on 75% system availability is 21 918 tonnes/day which at 1400 kg/m^3 equals 15 656 m^3/day.

   At a solids concentration by volume of 25% this requires 15 656 x 75/25 = 46 967 m^3 of water per day, for a total volume of 62 622 m^3/day, or 0.725 m^3/sec.

   The hydraulic evaluation, the results of which are given in Table 8.C.1 below, is performed for different pipe sizes starting with a velocity of approximately 3 m/sec.

   The steps to be taken for each line size are as follows:

   a. Determine the nearest line size which results in a velocity of 3 m/sec or over, - NPS 22 @ 3.25 m/sec.
   b. Compute Reynolds number for each line size given, using Equation 3.10 for water with density of 999.8 kg/m^3 and kinematic viscosity of 1.31 mm^2/sec @ 10° C. The Reynolds number = 1 321 714 for NPS 22 line.
   c. Compute friction factor, using Equations 3.12 or 3.14. Friction factor = 0.0129 for NPS 22 line.
   d. Compute pressure drop for water only, using Equation 3.4. Δp = 129 kPa/km for NPS 22 line assuming a figure of 0.046 mm for pipe roughness and 12.5 mm wall thickness.
   e. Estimate head loss of the slurry mixture using Equation 8.7 in the absence of laboratory test data.

TABLE 8.C.1

Pipe Size NPS	I.D. mm	V m/sec	Δp Water (kPa/km)	Δp Mixture (kPa/km)	Δp Line (kPa)
22	533	3.25	129	470	3055
20	483	3.96	212	479	3114
18	432	4.95	372	575	3738
16	381	6.36	705	855	5558

f. Multiply by pipeline length for system total pressure drop.

g. Calculate static head available due to the difference in elevation of 650 m. Static head available = 7014 kPa for a mixture density of 1100 kg/m^3.

An NPS 16 line would move the volumes and require no pumping. The velocity will be high at 6.36 m/sec and provision for surge relief at the bottom of the system is essential.

The water can be recycled and only make-up water will be required. Estimating a water loss of 10%, the system requires a volume of approximately 5000 m^3/day.

The mixture can be fed into the pipeline at the mine site at atmospheric pressure using a hopper and sluice arrangement.

At the rail loading site, the mixture would be dewatered using a travelling screen which would dump onto a conveyor for transport to the stockpile site.

Drainage water could be pumped back up to the mine site by a return water pipeline.

The make-up supply of 5000 m^3 day (3.5 m^3/min.) is assumed to be available from a local source.

Running the coal pipeline without power and valves would prevent the possibility of stoppages and surges which at the design velocity would be substantial and require a relief system.

3. *Equipment Requirements.* Major equipment and material requirements for the system are:

Coal Pipeline. 6.5 km of NPS 16 line pipe, Grade 360, 12.5 mm wall thickness.

Return Water Line. 6.5 km of NPS 16 line with minimum wall thickness of 6.4 mm, Grade 360 pipe.

Water Pumps. Centrifugal pump, electric drives, total power required 6000 kw.

Install (4) 2000 HP units in parallel (1 standby).

Electrical Power. High voltage power supply, substation and switchgear to operate pumps.

9. SLURRY DEWATERING

by

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Project Manager
Philips Barret Kaiser

9.1 PURPOSE AND SCOPE

The objective in dewatering a liquid/solids slurry in conjunction with pipelining is to return the solids to a condition wherein they can be stored, reclaimed and handled with the same ease as before being slurried. The ideal is not achieved without special treatment, dependent upon the size distribution of the solids. However, complete dewatering is not needed if the end use can be adapted to accept a moist product. For some end uses dewatering is not required.

9.2 TYPES OF SLURRY PIPELINES

These are arbitrarily divided into long distance and short distance pipelines. The latter can be a few metres or up to a few kilometres, say 3-5. Long distance pipelines can be measured in hundreds of kilometres.

The lines can be further divided into those handling a full size range of solids, from coarse to fine, and those handling fines only. Fines are here defined as 100 percent minus 1.4 mm (14 mesh). Intermediate size range of solids is 100 percent plus 0.5 mm (28 mesh) and minus 6 mm (¼ inch). Coarse solids are 100 percent plus 6 mm (¼ inch) up to the largest size particle the pipeline system can handle.

9.3 DEWATERING REQUIREMENTS

9.3.1 In-Plant Slurry Lines

The necessity for dewatering varies depending on the type of process involved. Plant feed is in slurry form because it was put into this condition at the discharge of the plant feed conveyor for ease in distribution to following process equipment. At some point in the process all solids will usually need to be completely dewatered. The definition of complete dewatering is that surface water will be removed as completely as can be accomplished by mechanical equipment. No thermal removal is included.

a. Coarse solids will be completely dewatered if they are not to be further beneficiated, or they will be beneficiated in a heavy media or heavy liquid process. They will be partially dewatered ahead of a water-based cleaning process such as a jig, if the removal of minus 6 mm solids is desired or if the amount of water going to the jig needs to be more closely controlled, or for both reasons.
b. Intermediate solids will be dewatered for the same reasons. In this size range the water-based beneficiation could be a jig or cyclones or vibrating tables, or one of several other processes.
c. Fines, defined as minus 0.5 mm, will be completely dewatered if they are not to be beneficiated and used raw. Following beneficiation they will normally be completely dewatered before being added to the coarser sizes.
d. When ships are loaded by pipelines from on-shore facilities it is necessary to remove excess water and return it to the shore. This will be done by decantation and will only be partial dewatering.

9.3.2 Between Plant Slurry Lines

The same reasons exist for dewatering as for "in-plant" lines. In addition, there is a need for storage ahead of the second plant in order to minimize dependence upon the first source with its built-in-production variances. The coarse and intermediate sizes would be stored in a dewatered condition whereas there is an option to store fines as a slurry or in a dewatered condition.

9.3.3 Commercial Pipelines

The solids being transported are fine, totally minus 1.4 mm, and generally the water is not compatible with the client's process, whether it is a chemical process or power plant. Dewatering is necessary. To what degree is not a generality. Power plants can dewater fine solids mechanically ahead of the pulverizers, or they could require thermally dried solids. Chemical plants could have similar requirements, as could liquefaction and gasification processes.

One answer to dewatering is to direct fire a high-density coal slurry. This slurry is generally considered to be 70 percent by weight of coal, 29 percent by weight of water and one percent by weight of patented stabilizers. Such slurries are very stable and can be transported and handled like oil. Their niche would be in replacing the oil used by power plants which had converted from coal firing sometime in the past and have lost their coal

handling and storage facilities or have let them become obsolete. Plants being newly designed to accommodate this fuel would also be a market.

The preparation of these slurries is a new technique, barely beyond the pilot state. Extremely fine crushing and grinding are involved and as clean a coal as can be produced is required in order to compete with oil on an ash and sulfur basis. A number of emerging physical coal cleaning techniques, which themselves are not out of the pilot stage, have potential advantages for the preparation step.

Coal-water slurries are discussed in numerous articles in the technical literature.

9.4 DEWATERING

Dewatering is a significant part of capital and operating costs. It represents approximately 50% of the total cost per tonne of coal. It can also cause problems when obtaining environmental approvals. Dewatering is accomplished through natural drainage when dealing with coarse solids. Intermediate sizes usually require the application of mechanical forces to arrive at a moisture content amenable to handling and storing. The fines can be dewatered partially using mechanical forces, but if a product is required which is essentially free of surface moisture, thermal dryers are a necessity.

Articles on mechanical dewatering have been published and can furnish information about the costs of the process. It is far less costly per tonne than thermal drying. However, when thermal drying is required it does not compete with mechanical dewatering as the latter cannot perform the function.

Capital costs for thermal drying can be of the order of $400,000 per tonne of evaporation. Operating costs, exclusive of amortization and interest, are of the order of $1.50 per tonne of coal input to the dryer. About two-thirds of this is in fuel cost and horsepower.

9.4.1 Dewatering Coarse Solids

Refer to Figure 9.1. A pipeline product containing the full range of sizes, from 100 mm to 0, first would be dewatered on a vibrating screen. The plus 6 mm portion, separated on a conservatively designed screen, should be of the order of 5 percent surface moisture, plus or minus a percent depending on the average particle size in this fraction and the specific gravity of the solids. Screen manufacturers usually size their equipment very conservatively for this use. Competition is keen enough to assure efficient, economic, effective installations.

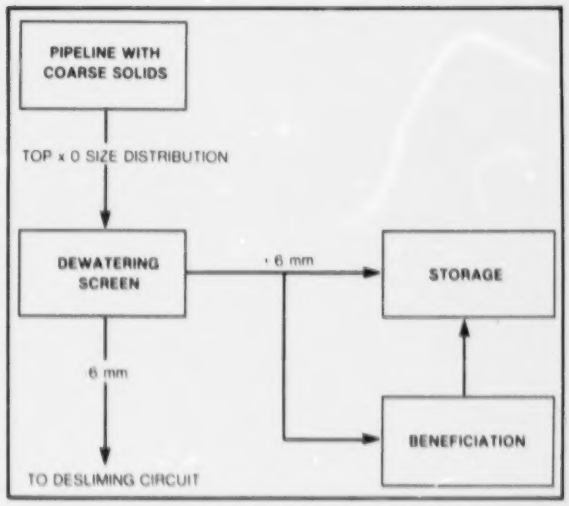

Figure 9-1 Coarse solids dewatering

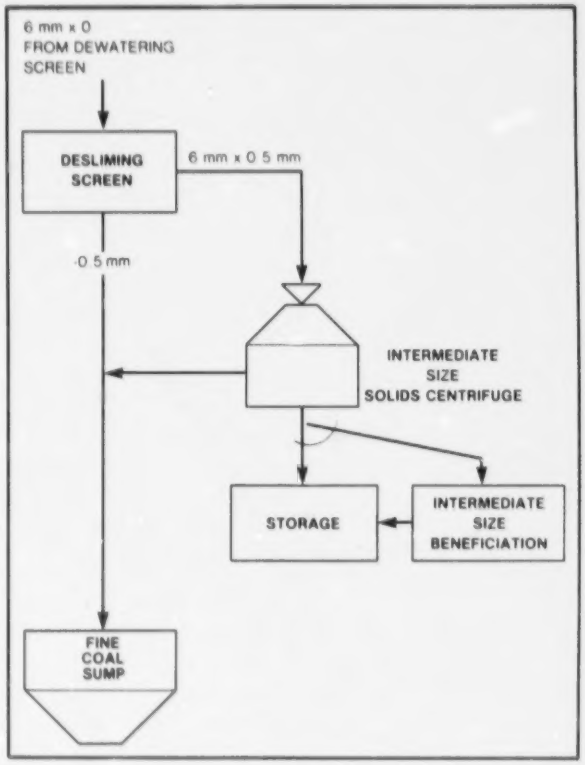

Figure 9-2 Intermediate solids dewatering

9.4.2 Dewatering Intermediate Size Solids

Refer to Figure 9-2. This range can be dewatered on a vibrating screen to a surface moisture content of 9-15 percent, depending on the average particle size and specific gravity of the solids. Further dewatering would be accomplished in a centrifuge. The usual choice is a horizontal or vertical vibrated basket centrifuge and the product surface moisture can be as low as 2.5 percent, but would generally be 4.5 - 5.5 percent. Surface moisture is dependent on the average particle size and the solid's specific gravity.

Non-vibratory centrifuges will also dewater this size range to approximately the same moisture level. Their

main disadvantage is maintenance because they use a spiral or plow to discharge the solids and keep them moving through the machine. Thermal drying is not generally a requirement since these solids, having a moisture content of around 5 percent, are easily handled. When they are included in the thermal dryer feed stream, it is usually in order to keep the real fines (minus 0.5 mm) from caking in the dryer.

9.4.3 Dewatering Fines

Refer to Figure 9-3. The greatest dewatering problem is with this size range, minus 0.5 mm. Mechanically, these solids can be dewatered to approach 12-14 percent surface moisture. At this moisture, handling problems are created at conveyor loading and transfer points. The low surface moistures above would apply to a rather coarse size - about 0.2 mm average particle size - and a machine feed moisture of around 40 percent concentration by weight. The product surface moistures would generally be in the 18 to 25 percent range. Solids at the latter moisture are a real handling problem, being capable of adhering to vertical surfaces.

Any device used to dewater this size range will pass ultra fines to some extent. Screen type centrifuges will pass the most and vacuum or pressure filters the least. The more ultra fines lost to the effluent, the lower the surface moisture of the product. Thus screen bowl centrifuges will give the lower moisture products and the vacuum filters the higher moisture products. Solid bowl centrifuges can be operated to minimize solids loss but the product moistures are high. If solids losses are permitted to increase, the cake moisture is reduced. Vibrating screens of the high frequency, low amplitude design can reduce surface moisture to the order to 30-35 percent, but with loss of minus 0.15 mm solids. Vibrated, or rapped sieve bends would produce similar results. For both, the screen decks easily become blinded and the cake moisture is high because the ultra fines stay with the screen oversize. These units require maintenance and operator attention. One advantage for sieve bends is that they will accept a much more dilute feed than the high speed dewatering screens.

9.5 MECHANICAL DEWATERING EQUIPMENT

The methods are many and overlapping. Figure 9-4 illustrates the choices of dewatering devices for the coal industry and the sizes of particle to which they are most applicable. Equipment such as cyclones, sieve bends, sludge tanks, spiral rakes, Vor-Sivs and static thickeners, do not produce a final product but are used in conjunction with screens and or centrifuges or filters. They are useful in removing large amounts of water. The results given in Figure 9-4 are for coal. Higher or lower specific gravity solids would have different values. Generally, the higher gravity solids would have the lowest surface moisture. Solids which retain moisture, such as clays, are exceptions.

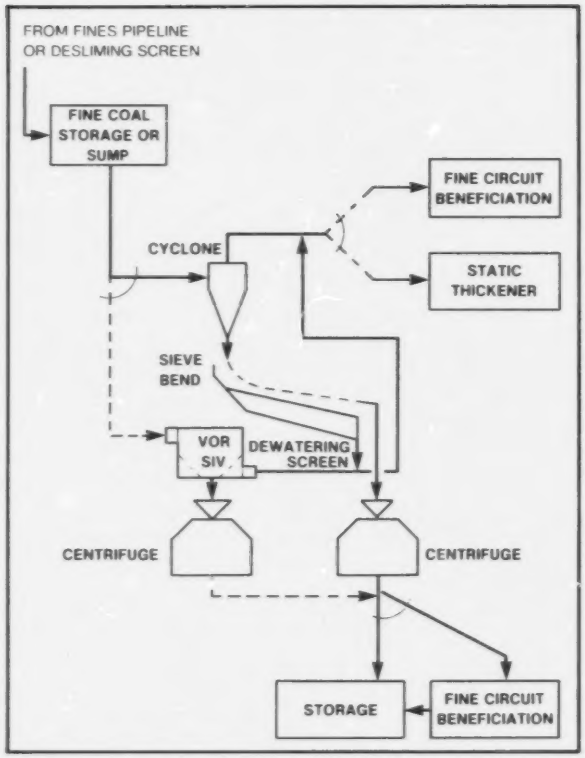

Figure 9-3 Fine solids dewatering

9.5.1 Vibrating Screens

These can dewater coarse sizes sufficiently to satisfy most end use requirements. Surface moistures would be of the order of 4-5 percent.

Intermediate size particles would be dewatered on vibrating screens to about 8 to 14 percent surface moisture. These are not generally satisfactory for end use and further treatment by centrifugal machines is necessary. In the case of dewatering ahead of a cleaning circuit this degree of moisture removal is all that is necessary.

Fine sizes can be partially dewatered by high speed vibrators at the cost of losing ultra fines through the screen apertures. Ahead of a cleaning circuit this is generally acceptable. If it is to be the final product or is the feed to a thermal dryer, additional dewatering by centrifugation is needed. Surface moisture from the high speed vibrators would be in the range of 25-35 percent, depending on specific gravity and average particle size.

9.5.2 Centrifuges

These are classified in several ways but basically according to whether or not they use screens. The number of "G's" developed also is a distinction, high "G" force or low "G" force. "G" is the force of the acceleration of gravity. The screen type of centrifuge is further divided into:

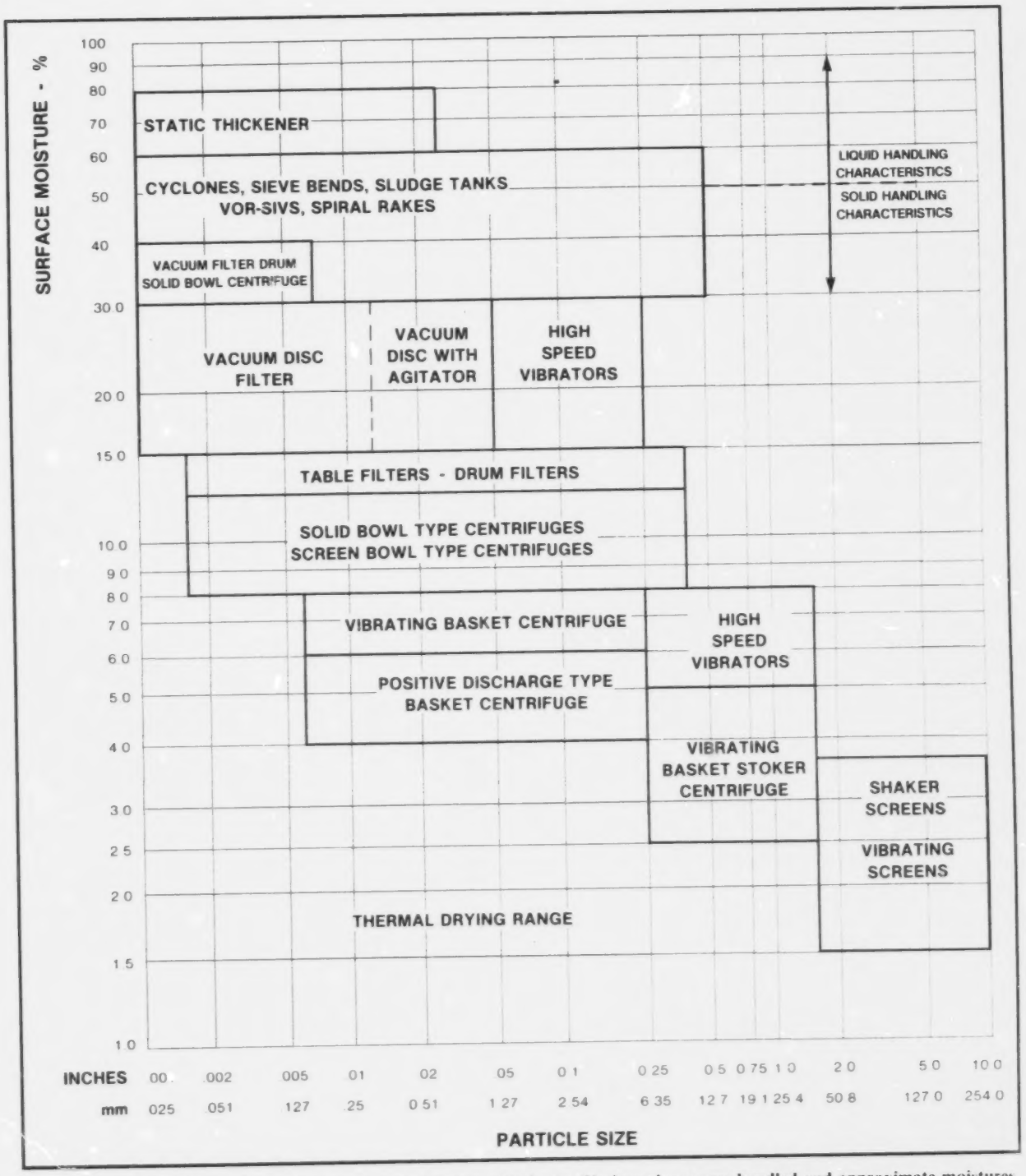

Figure 9-4 Dewatering equipment in common use in the coal industry (Various size ranges handled and approximate moistures produced)

a. basket without transporting device,
b. basket with transporting device,
c. vibrating basket - horizontal or vertical.

Generally coarse sizes above 12.5 mm (1 2") do not need centrifugation so they are separated on the vibrating screen and bypassed. Plus 0.5 mm (28 mesh) solids with a

top size of 9.5 to 12.5 mm are usually processed through a vibrating basket type centrifuge and the product surface moisture for coal (specific gravity 1.4) would be 3-5 percent depending on the average particle size and the absence of minus 0.5 mm solids.

Fine size coal solids are dewatered by basket type or solid bowl type centrifuges, with transporting devices, to a surface moisture of 14-18 percent. The centrifuges can be horizontal or vertical. Ultra fines - minus 0.15 mm - would pass through the screen and would have to be re-collected and dewatered by other means. The solid bowl would retain most of the ultra fines, however.

The ultra fine coal solids are settled in a static thickener, usually together with minus 0.5 mm solids, and dewatered by vacuum or pressure filtration. Tailings solids in this size range can be settled in static thickeners and dewatered by vacuum filtration, solid bowl centrifuges or pressure filters.

9.5.3 Filters

These are vacuum or pressure types. The most commonly used is the rotary disc vacuum filter. It will do its best dewatering when fed a normal 0.5 mm x 0 size distribution in a 40 percent concentration slurry. This is ideally the settled solids from a static thickener. The product moisture is mostly dependent on the size distribution and on the vacuum pressure available. Speed of rotation is also a factor, as is the volume of air drawn through the solids and filter cloth. For coal under normal conditions the surface moisture can be 20-22 percent. It can go to 25 percent with an abnormal amount of minus 0.044 mm solids in the feed and a high ash content. Tailings containing many clay fines would probably be filtered on a vacuum drum filter because the cake is thin and high in surface moisture, 28-32 percent.

Tailings can be dewatered by belt pressure filters to a lower surface moisture than by vacuum drum or disc. A much lower surface moisture can be obtained for tailings by using a plate and frame pressure filter. The product is discharged in a large, tightly packed block and is easily handled.

9.5.4 Thickeners

This is a device which uses gravitational forces to settle fine solids from a slurry and separate them from the bulk of the water. Sieve bends, Vor-Sivs, sludge tanks, cyclones and spirals are in this category. Their product is not a dewatered mass of solid particles but a thickened mass in which the solids concentration is normally 25 to 60 percent by weight depending on many factors. The separation of solids and water is not absolute and the ultra fine solids, minus 0.044 mm usually, are difficult to settle out. Chemical reagents (flocculants) are used to agglomerate these sizes and assist gravitational settling.

A static thickener, because of much longer retention times and virtual lack of disturbing turbulence, can make a good separation of solids from water. Depending on the specific gravity of the solids, the shape of the solids, reagents used and the average particle size, the separated water can be clean, containing in the order of 50 ppm of solids. Normally it will be 300-400 ppm. The settled solids can be further treated by filtration, centrifuging or by being pumped to a long term settling pond.

9.5.5 Cyclones, Vor-Sivs and Sieve Bends

Some brief description of these devices is necessary because they are not as common as other equipment.

a. Cyclones. These are devices having a cylindrical feed section and a conical concentrating and discharge section. Feed slurry is delivered under pressure tangentially into the cylinder. The solids are thrown towards the wall by the centrifugal force of the rotating mass and slide down to the conical apex where they are discharged with some of the water. The bulk of the water and the ultra fine solids which stay with the water (the actual size is dependent on the solid specific gravity and the centrifugal forces in the cyclone) are drawn up through the cylindrical vortex finder and removed from the cyclone. Size separation is usually about 0.15 mm to 0.07 mm depending on the cyclone diameter. Factors influencing separation in the cyclone are cyclone and apex diameters and the cone angle to a lesser extent. A vortex of air extends throughout the length of the cyclone. Any of several manufacturers will assist in the application of the proper cyclone to a specific purpose.

b. Sieve Bends. These are stationary wedge bar screens with the bars oriented at 90 degrees to the flow of slurry and the screen surface curved in a 45 degree or 60 degree arc. The curvature of the screen causes the edge of each subsequent wedge bar to cut off a slice of the slurry having a thickness of one-quarter to one-half of the slot width. Only solids small enough to be in this stream will be lost through the screen. The bulk of the solids and some water are discharged over the end of the sieve bend. There are minimum feed conditions which contribute to the proper functioning, such as a well distributed slurry across the screen width and a slurry velocity equal to a 0.76 metre head.

c. Vor-Sivs. These are devices that have features of both the cyclone and the sieve bend. They are larger diameter circular screens fed horizontally and tangentially with a slurry under about 1.5 metres of head. The centrifugal action of the rotating mass of slurry forces water and appropriate sized solids through the screen apertures. Incoming feed forces the mass to spiral downward. An inverted conical screen forms the lower half of the device and concentrated solids are discharged through the apex of the cone. Water and fine solids continue to discharge through the conical screen. The Vor-Siv performance is quite sensitive to change in feed rate and head.

9.6 THERMAL DRYING

If the need is for dry solids, with maximum surface moisture of about 7 percent, thermal drying is required. At the end of the Cadiz to Cleveland pipeline of Consolidation Coal Company (operated from 1957 to 1964) the fine coal was thickened as described above and then thermally dried before being pulverized for feeding the boilers at Cleveland Electric Illuminating Company. In this instance flash dryers were selected. This type of dryer can process about 90 metric tons per hour. The nature of the dryer is to entrain all of the solid particles in hot gases. The coarser solids are captured in large diameter air cyclones and the ultra fines must be collected by bag filters or highly efficient wet scrubbers. The latter cause a problem because the scrubber effluent must be treated and returned to the system. An alternative would be to use a fluid bed dryer. However, on all fine feed it would approach an entrainment type dryer. The advantage of a fluid bed dryer is that it can handle larger feed quantities and evaporate larger quantities of water. It still has the scrubber problem.

If capacity requirements are not excessive, use of a helical flight conveyor type of dryer, with hot oil pumped through the flights and shaft, can be selected. There is very little lost ultra fines and a bag collector could be used because the drying temperatures are moderate. Another thermal drying unit designed especially to handle fine size solids is the type which uses a porous conveyor to transport the solid particles through the drying chamber. Air pulled through the conveyor gently fluidizes the solids and provides optimum opportunity for the discrete particles to be surrounded by hot gases. A scrubber or bag collector is required to capture ultra fines entrained by the fluidizing air.

10. SLURRY TESTING

by

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10.1 GENERAL

If the slurry exists, as in the case of slurries in an operating industrial plant, choosing whether or not to conduct a test program is essentially an economic decision. The benefits of testing are obvious; for turbulent flows, energy consumptions per unit mass transported vary approximately as the square of the velocity and operation at the lowest velocity (just above deposition) minimizes energy costs. For small pipes or short distances the cost of testing may not be justified, but for large pipes and or long distances, significant savings may be possible. Because of the importance of particle size distribution and the effect of minor constituents on deposition velocity, whenever practical experience suggests that predictions from the nomogram of Figure 7-5 are conservative (high), a testing program is likely to indicate lower energy consumptions are possible.

An additional benefit of low operating velocities is that they minimize erosive wear for locations in which the flow has a finite velocity component normal to a solid boundary. These situations arise in and downstream of pumps, valves, bends and other fittings. Minimizing these wear rates minimizes maintenance and downtime costs, which are often more important than the cost of the eroded components. On the other hand, pipe wall wear rates for truly parallel flow depend primarily on the total solids throughput so there is less disadvantage in high pipeline velocities for long, straight lengths of pipe. However, testing may be required to determine the operating lifetime of such sections. Simulations of erosive wear processes may be used to compare alternative materials of construction but these simulations should take the particle trajectories into account. Thus for situations in which impact erosion is likely to be dominant, the rotating device of Reference 1 would be useful. For abrasive pipe wall wear, the particle motion should be parallel to the wall, however. Although laboratory pipeline wear rates have been conducted, these tests require large quantities of solids and are of comparatively long duration, two serious disadvantages.

10.2 RHEOLOGY

The primary purpose of testing, however, is to establish the hydraulic performance of the slurry in the conditions for which stable, trouble-free operation is necessary. A classification of slurry flows has been given in Chapter 7 and the type of slurry influences the choice of test program. Truly homogeneous flows occur with slurries of negligible settling tendency and show high resistances to flow so that test data are essential for design. Either concentric cylinder (Couette) or tube viscometry can be used in these tests and the data are fitted to the integrated relationship which is most satisfactory. The integrated tube flow relationships were given in Chapter 7 as Equations 7.2 and 7.6 for the cases of Bingham and power law fluids respectively. For Couette viscometers the measured variables are the torque (T) at the inner cylinder and the speed of rotation (ω). The corresponding integrated relationships, if the inner cylinder rotates, are for Bingham fluids

$$\omega = T[1/r_1^2 - 1/r_2^2]/4\pi L\mu_p - \tau_y \ln(r_2/r_1)/\mu_p \qquad ...10.1$$

where L is the effective height of the inner cylinder, and for power law fluids

$$\omega = (n/2)(T/2\pi KL)^{1/n}[(1/r_1^2)^{1/n} - (1/r_2^2)^{1/n}] \qquad ...10.2$$

Turbulent flow in the viscometer annulus can occur at high Reynolds numbers and data always should be examined for this possiblity. Criteria for the transition are given in Reference 2 for Newtonian fluids. Since slurries are usually non-Newtonian, these criteria are only rough guides. For Bingham fluids, the plastic viscosity should be used in the Reynolds number. Again, it is important that the coefficients in the models be determined at the proper shear stresses. This restriction is more easily satisfied with Couette viscometers than for tube flows. On the other hand, homogeneous slurries often display time dependent effects in Couette viscometers which do not occur in tube or pipe flow. These complications seem to be associated with the small sample volume and may be due to particle migration, viscous heating or secondary flow effects.

10.3 TEST FACILITIES

Because of such practical difficulties with viscometry, a small test pipeline (D = 50 mm) is usually preferable,

even for homogeneous slurries. The volume of slurry required is, of course, larger than for viscometry but if the test circuit contains no reservoir (closed loop operation) it still corresponds to only a few metres of pipe. By varying the velocity over wide limits, both laminar and turbulent flow can usually be produced. In view of the problems associated with the turbulent and transition regions described in Chapter 7, this experimental evidence is invaluable in design.

For all other slurries, pipeline tests are certainly desirable because they provide deposit velocities and these cannot be predicted reliably. If these velocities are to be scaled for larger pipes, the nomogram of Figure 7.5 and / or the correlation of Equation 7.18 can be used, with their attendant approximations. Of course, full scale tests are preferable in all cases because of the uncertainties in scale-up of both head losses and deposit velocities.

Sometimes, viscosities are required for modelling purposes with slurries which give flows with some heterogeneity. At low concentrations both tube and Couette viscometry are often difficult for such slurries because of settling effects. If settling is less severe at high concentrations, these approaches can be used and the rheological data fitted to a concentration-dependent relationship of an accepted form. Alternately, it may be possible to infer the effective viscosity from the turbulent flow, high velocity head losses because these flows may be pseudo-homogeneous (see Chapter 7). Removal of the coarse, rapidly settling particles is not recommended because the remaining slurry will have a different viscosity-concentration relationship and the difference cannot be quantified.

With high slurry viscosities or coarse particles, it is desirable to monitor pump efficiency during testing. Reduced efficiencies are known to result in both cases but quantitative predictions of these effects are not possible. With reliable efficiencies and accurate head loss predictions, capital costs of excess capacity can be minimized and this is the second advantage of testing.

In addition to viscometry and pipeline flow measurements, the properties of the particles (density and size distribution) should be determined in the test program. Densities are required for fitting the data to a model and the size distribution also may be useful in this regard. However, the size distribution is really required to define the conditions of the test to prevent misapplication of the results.

Because of interest in understanding flows of special importance, it may be desirable to determine kinematic coefficients of wall friction (η, values), concentration distributions or velocity distributions. With such measurements one can take advantage of mechanistic models for purposes of scale-up.

Differences in roughness between test pipelines and those in operating plants will often exist and the effect of these differences is of interest. Although experimental evidence is limited, it appears that ϕ values (see Chapter 7) obtained in smoooth pipes can be used with fully rough pipes. In mechanistic models, this means that the local slurry viscosity should be used in predicting the velocity.

It is important to note that the number of specialized laboratories devoted to slurry testing continues to increase. At present, most countries with mineral processing industries of any scale have such facilities. This development is evidence that plant instrumentation is inadequate for slurry characterization. Invariably, it is more efficient to remove samples of the slurry for testing in facilities whose instruments have been designed and calibrated for that specific purpose. Of course, liaison between the test facility and the plant operating personnel should be close. However, testing is a specialized activity which can be done most economically by those with long experience.

10.4 REFERENCES

1. Hoey, G.R., and Bednar, J.S., *Report ERP/PMRL 81-18 (TR)*. Energy, Mines and Resources Canada, Ottawa, 1981.
2. Bird, R.B., Stewart, W.E., and Lightfoot, E.N., *Transport Phenomena*. J. Wiley, New York, 1960, p.96.

APPENDIX 10-1 DETERMINATION OF μ_p AND τ_y

The viscometric data shown below was obtained with a Couette viscometer for which (inner cylinder rotating):

r_2 = 0.021 m
r_1 = 0.0184 m
L = 0.0613 m

Torque (N•m)	ω (sec^{-1})
3.98 x 10^{-2}	53.6
3.07	26.8
2.53	13.4
2.01	6.7
1.80	3.35

Equation 10.1 may be written

$$\mu_p\omega = AT - B\tau_y$$

where in this case A = 890.7 m^{-3}
B = 0.1322

Use non-linear regression with N points:

$$\mu_p\Sigma\omega = A\Sigma T - NB\tau_y \quad (1)$$

$$\mu_p\Sigma(T\omega) = A\Sigma T^2 - B\tau_y\Sigma T \quad (2)$$

From the data given

$\Sigma\omega$ = 103.9 S^{-1} — NB = 0.661
AΣT = 11.93 N m^2 — $\Sigma(T\omega)$ = 0.349
AΣT^2 = 0.0346 N^2 m — BΣT = 1.77 x 10^{-3} Nm

Substituting

μ_p = 0.0379 N•s/m^2 (Ans)
τ_y = 12.15 Pa (Ans)

11. ENGINEERING STANDARDS

by

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11.1 INTRODUCTION

The safe and economic performance of pipeline systems is important to industry, governmental or regulatory authorities and the general public. To achieve those objectives, pipelines are built and operated in accordance with national standards or codes which have superseded, or have been evolved from, earlier industry developed standards. In some cases the regulatory authorities have drafted pipeline regulations which have more stringent requirements than those laid down in the industry developed national standards. Where both the American National Standard Institute (ANSI) pipeline codes and the Canadian Standards Association (CSA) pipeline standards are considered safety codes which mainly address operating and construction practices, the government regulations also address the environmental and socio-economic aspects of pipeline systems. While national codes and standards for oil and gas pipelines have been fully developed in the United States, Canada and several other countries for considerable periods of time, work on the development of codes for slurry transportation systems has only recently begun. The codes and standards used in the industry in Canada and the United States have been prepared by industry associations using technical committees composed of personnel of member companies and or individual members with expertise in the areas involved. Such committees also provide ongoing scrutiny and updating of the codes and standards. Canadian pipeline standards are prepared by CSA, while in the United States there are a number of institutions. The American Society of Mechanical Engineers (ASME) which prepares the ANSI piping codes, the American Petroleum Institute (API) and the American Society for Testing of Materials (ASTM) are agencies most frequently involved with the pipeline industry.

The purpose of national codes and standards for pipelines in the U.S. and Canada is to provide minimum standards of design, materials, selection, fabrication, installation, inspection, testing, operation, maintenance and repair of pipeline systems. Some of these aspects are covered also by government or autonomous regulatory agencies, who generally incorporate the codes by reference in their regulations. National codes and engineering standards are effective in ensuring uniformity of quality of pipeline installations and in minimizing hazard, risk of failure and eventual damage to life, property and the environment.

Most of the problems encountered in liquid pipelines are present in pipeline transport of slurry over long distances. The presence of solids of different characteristics in various size, shape and distribution, compounds design, operation and maintenance problems. Although most water based slurries are less hazardous than conventional liquid petroleum products, slurry systems can involve similar hazards in special circumstances such as: cases in which the carrying medium is a hydrocarbon product, or in the event dry pulverized coal dusts are handled at some point in the slurry preparation or dewatering and delivery areas. A broad spectrum of operating conditions can exist in slurry systems, depending on the nature, concentrations and behaviour of their solid and liquid components. The whole range of conventional pipeline materials and equipment has found application in these systems, as well as a new generation of slurry processing and handling devices designed for the specific needs of an array of slurries, such as coarse or fine slurries, high low concentrations, suspensoids in chemically adjusted media, and tailings. The nature (composition, size, shape, hardness, etc.) of the solid components such as pulp, iron ore, limestone, copper concentrates, phosphate concentrates, coal and other minerals and the operating conditions (pressure, temperature, velocity, pH, corrosivity, etc.) determine material selection to withstand corrosion and erosion wear and eventual service life.

The development of national codes of slurry pipeline systems and basic requirements of safety and performance standards for principal system components are discussed in this chapter. Regulatory aspects are discussed in

Chapter 16. A list of applicable reference code standards and specifications are included at the end of this chapter.

11.2 PROPOSED SLURRY PIPELINE CODES

Existing liquid petroleum pipeline codes have been used for slurry pipeline systems built to date. Work on the development of slurry pipeline codes in the U.S. and Canada is nearing completion. Adequate guidelines and minimum standards are provided by the ANSI code for Pressure Piping B.31.4 "Liquid Petroleum Transportation Piping System" and by the CSA code Z183 "Oil Pipeline Transportation Systems - Pipeline Systems and Materials", to cover all important aspects of petroleum liquids transportation. With a number of proposed slurry pipeline projects in the U.S., the Slurry Transport Association initiated a program in 1977 with the ANSI B.31.4 Management Committee for the preparation of a suitable slurry pipeline code. A subcommittee was formed to draft the code designated B.31.11 "Slurry Transportation Piping Systems". The subcommittee started its work in 1978 and has since progressed through study, wording and review by the different work groups of the various sections. The liquid petroleum code B.31.4 was used as a basis for structure and format of the new code. A final draft of the B.31.11 code was approved for publication by the main B.31 committee late in 1984 and the code is now expected to be published late in 1986. The new U.S. B.31.11 slurry pipeline code is a "stand alone" code which very closely follows the outline and clauses used in the B.31.4 "Liquid Petroleum Transportation Piping Systems" code and in many areas duplicates the exact wording of the clauses used. One notable difference between the slurry pipeline code and the liquid petroleum code is the design factor used for maximum operating pressure. For water based slurries a design factor of 80% is used instead of 72% as in B.31.4.

In the U.S. several large slurry pipeline projects have been studied for nearly a decade now and the initial effort to produce a slurry pipeline code has been directed towards large, long distance coal-water slurry pipelines. In Canada the feasibility of various slurry pipelines has been studied for about the same period of time and has included the study of movement of Western Canadian coal to Central Canada as well as to the West Coast.

As the need for a Canadian pipeline code or supplement to an existing code for slurry pipeline systems is apparent, the CSA through its Z183 "Oil Pipeline Transportation Systems" code technical committee established a slurry pipeline code task force in 1983. The task force findings were reported to the Z183 committee in 1984 and a slurry pipeline code subcommittee (to Z183 committee) was instituted late in 1984.

One of the first tasks of the subcommittee was to establish a concensus and recommend to the Z183 technical committee the form the slurry code should take. Although it is too early to tell which direction the work will take, indications are that the first CSA slurry pipeline code will be a supplement to the Z183 code. The supplement would describe exceptions, changes and or additions to the requirements listed in Z183 and adopt and leave unchanged the clauses common to both systems.

Since no timetable for completion of a code exists, any slurry pipeline to be considered in the immediate future probably would be designed in accordance with CSA Z183. If an application were to be submitted to a competent regulatory agency (i.e., the Canadian Transport Commission, refer to Chapter 16), the agency could in consultation with the proposing company decide to use CSA Z183, ANSI B.31.11 or possibly a compromise between the two codes if it were found that the use of Z183 would result in an inappropriate system design.

It should be borne in mind that all codes are basic safety standards, giving minimum standards for normal conditions only, and should be amended accordingly where circumstances require.

11.3 SAFETY AND PERFORMANCE STANDARDS

Major factors affecting safety and performance of components of a slurry pipeline system over its design life are the following:

a. materials,
b. design criteria,
c. quality control during manufacture,
d. quality during construction,
e. corrosion erosion monitoring and protection.

11.3.1 Materials

Materials testing and selection provisions of the liquid petroleum codes ANSI B.31.4 and CSA Z183 are presently adequate for line pipe, valves, flanges and fittings required in a vast majority of slurry pipeline applications. With on-going R and D efforts it is anticipated that areas of possible improvement, which are indicated by operating experience, will be addressed by newly developed materials and processes. One important area is service life of components in systems that deal with abrasive slurries. Development of special materials and surface treatment of components are under way to provide longer life in high wear areas of such systems. Special attention to the effect of the solid particles of the slurry similarily has to be given in the materials and design selected for the moving parts in contact with the solids in valves, pumps, feeders and other equipment of the system, in order to achieve expected service life and prevent premature failures.

a. Line Pipe. The available range of American Petroleum Institute (API), ASTM and the CSA Z245 line pipe codes and standards normally used in the petroleum industry fulfills the requirement of slurry pipelines. For particularly abrasive slurries, increasing use is being made of recently developed steel pipes hardened to 500 plus Brinell on the inside.

b. Valves. Operating experience with high pressure slurry valves indicates there is room for improvement in the design for abrasive slurries. Ball and plug valves of the conventional type conforming to the API Standard 6D "Steel Gate, Plug, Ball and Check Valves for Pipeline Service" and CSA Z245.15 are normally used. Operational problems are faced with the current design, for example, solid particles could plug cavities, seats and trunions of the ball valve, requiring dismantling for repairs. Better designs permitting tight shut-off are needed to ensure performance for high pressure slurry service.

c. Fittings. Fittings conforming to dimensional standards of ANSI, API, CSA and the Manufacturer's Standardization Society of the Valves and Fittings Industry (MSS) are acceptable for use on slurry systems provided operating conditions are considered in selecting the type suited for the service in keeping with good engineering practice. With heterogeneous settling slurries and under particular flow conditions excessive wear can result on wear prone sections, such as bends and changes in direction. Special design provisions, such as long radius bends or wear resistant materials, are employed to ensure safe operation.

d. Pumps. Design and application of pumps for slurry service are covered in Chapter 6. Although there are no design or manufacturing standards specifically for slurry pumps, the API has published a number of standards for pumps used in the petroleum industry which probably would be followed.

   API Standard 610 covers "Centrifugal Pumps for General Refinery Service".

   API Standard 674 covers reciprocating positive displacement (PD) pumps and API Standard 676 covers rotary PD pumps.

   As discussed in Chapter 6, centrifugal pumps as well as positive displacement pumps have shortcomings for large volume and high pressure slurry pipeline service.

   Design work is continuing to develop higher volume PD pumps and higher pressure centrifugal pumps to provide a new generation of pumps with capabilities that are an order of magnitude above the current limits.

11.3.2 Design Criteria

The design criteria for the majority of equipment available for slurry pipelines have been established for use in the petroleum and natural gas industries. Until the slurry pipeline industry matures and there is a sufficient demand for specific performance requirements, the situation is unlikely to change. The designer of a slurry pipeline system will have to select the best suitable equipment for the purpose, recommend modifications, and equipment will evolve as demand and applications grow. The development of slurry pipeline pumps from equipment originally designed for the drilling industry (refer to Chapter 6) is a typical example. Design criteria for slurry pipelines, as in the case of oil and gas systems, addresses integrity and safety of the pipeline in two broad requirement groupings. The first pertains to ambient and operational conditions such as temperature, pressure, buoyancy and pipe-soil forces. Pipe-soil forces are caused by phenomena such as pipe movement, soil erosion, land slides and earthquakes. The second set of design requirements concerns external impacts and forces. This second set is generally minimized by suitable depth of cover, added pipe wall thickness or casings and operational procedures such as surveillance.

11.3.3 Quality Control

Methods to control quality of equipment and materials required for a slurry pipeline are unlikely to differ much from those employed for other pipelines or industrial installations. Mechanical, electrical and control equipment is manufactured in accordance with specifications which may vary from general specifications as given in the applicable industry standards to detailed specifications for specific equipment. Purchasers employ a system of plant progress inspection and performance tests, usually specified at time of purchase to ensure that specified criteria are met. During the installation or field construction phase of the project, quality control inspectors are employed by the owners to monitor the performance of the contractor(s) engaged to construct the facilities and to ensure that the workmanship meets the specified requirements. In the case of pipeline construction these requirements would be those specified in the applicable CSA Code Z183 or Z184 or other appropriate national standards supplemented by any specifications the owners of the system may desire.

11.3.4 Corrosion/Erosion

The amount of wear due to corrosion, erosion, or a combination thereof is difficult to quantify. It would be difficult and even unwise to try to quantify design factors or other figures having the effect of increasing pipe wall thicknesses by a specific amount to allow for material loss or wear by corrosion/erosion. Current codes such as the soon to be released ANSI B.31.11 specify that, in the design of the system, allowances should be made for erosion/corrosion wear if such is anticipated. Suppose a pipe wear number was specified in a code for specific materials or operating conditions and a system was built using the specified factors. If the pipeline system shows excessive wear or failure in less than the specified life, it is not inconceivable that the authors of the particular standard could be sued for damages. The codes however, could specify that designs submitted for regulatory approvals do include a reasonable design factor for corrosion/erosion and that the system be protected by anti-corrosion systems or additives (refer to Chapter 8).

11.4 LIST OF CODES AND STANDARDS

The list of codes and standards which currently apply to the design and construction of slurry pipelines is very short when taken in the strict sense, however the applicable codes do refer either specifically or by inclusion to a large number of other standards and codes, both Canadian and American, which could or may be applicable. Currently there are no CSA Standards for slurry pipelines. It is generally understood that CSA Z183 requirements would apply if an application for a slurry pipeline were made. In the United States the new ANSI Code B.31.11 is expected to be published late in 1986. Based on the above background, the list of current codes is as follows.

11.4.1 Primary Codes

Canada - CSA Z183 "Oil Pipeline Transportation Systems". USA - ANSI B.31.11 "Slurry Transportation Piping Systems".

11.4.2 Related Codes

Codes and standards may be applicable to parts of a pipeline system such as storage facilities, pump stations, utility plants and electrical installations. CSA Standard Z183 lists a number of them as "Reference Publications" in Section 1.2.

11.4.3 Material and Dimensional Standards

In addition to the safety codes and standards, there are large numbers of material and dimensional standards which specify manufacturing standards and/or dimensions for such items as pipe, fittings and flanges, valves, bolting, structural materials and welding electrodes. These standards are issued by an equally large number of industry and manufacturers' associations and committees in the United States and Canada (and other developed nations). The most common North American ones are:

a. ANSI (American National Standards Institute),
b. API (American Petroleum Institute),
c. ASTM (American Society for Testing of Materials),
d. MSS (Manufacturer's Standard Society),
e. CSA (Canadian Standards Association).

A very complete list of these publications may be found in CSA Standard Z183 in Table 4.2.

12. CONSTRUCTION PRACTICE

by

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12.1 INTRODUCTION

Unlike the construction of other facilities, pipeline construction is a mobile operation which, ideally upon completion, has very little to show for the effort expended. Construction of slurry pipelines should be no exception and procedures are the same as for any other cross-country pipeline. It is recognized that not all slurry pipelines are long distance or below ground and, in the case of in-plant lines or other shorter lines, the construction practice would follow those used for that type of construction.

Construction practices for long distance oil and gas pipelines have changed little in the last two decades, with the exception of welding techniques where the semi-automatic welding process is being used on an increasing number of the larger diameter pipelines. Construction equipment has increased in size with the requirements to lay larger diameter pipelines and has become more sophisticated. There is no reason to assume that the techniques used for the construction of slurry pipelines would differ significantly from current oil and gas pipeline practice.

The following sections describe the construction practices normally used for long distance pipelines and which quite frequently are used for shorter, 5 to 10 km lines as well.

12.2 PRECONSTRUCTION ACTIVITIES

Before the system design can be finalized and construction started, the location of the pipeline has to be finalized and arrangements made with owners of affected properties for lease or purchase of the necessary lands.

12.2.1 Route Selection

Route selection has been covered in Chapter 8, however some emphasis could be placed here on the topographical constraints due to the stringent slope requirements. It is essential during the route selection process and the on-site route reconnaissance that this slope requirement is kept clearly in the forefront.

12.2.2 Land Acquisition

As the pipeline route alignment is being finalized, property ownership lists are prepared and easements are negotiated. Ownership data and any special requirements such as the disposal or salvage of timber or topsoil handling are incorporated in a "line list". Where no agreement can be reached with a landowner, the route may be either relocated or expropriated in accordance with provisions of the laws of the appropriate jurisdiction.

Land generally is acquired sufficiently far in advance of requirements to ensure that the construction activities are not affected due to lack of easements through any given property. It is becoming more and more a pre-requisite of the regulatory authorities that, where practical, easements are obtained before the permit applications are submitted.

12.2.3 Survey

A legal survey of the pipeline route is performed during the land acquisition process. Prior to the start of construction, the survey is re-established and the pipeline centre line staked. Any stakes destroyed after the initial survey are then replaced and any final adjustments required in the alignment are made at this time. Temporary bench marks and reference points are established at key locations such as road and stream crossings. An as-built survey is performed either during or after completion of the construction.

12.2.4 Construction Tenders

Construction tenders are invited from qualified contractors. In general, the contractor will bid for the construction phase only, with all major materials and pipe provided by the owners. As all materials are either already stockpiled or their delivery is confirmed at the time construction tenders are called, a contractor can move in and "kick off" construction within days from award of contract.

12.3 Conventional Construction Activities

Immediately upon award of a contract the contractor moves his equipment and field personnel to the location and starts work. The procedure followed can be broken down into a number of operations.

12.3.1 Clearing

Generally the total width of the right-of-way is cleared unless otherwise stipulated on the line list.

Clearing is usually carried out by standard construction equipment, primarily dozers with special cutting blades and rakes, wherever regulations permit machine clearing. Cleared timber may be retained for rip-rap, as required, and the balance is disposed of in a proper manner.

Where required by provincial forestry regulations or individual landowners, clearing is performed manually and all merchantable timber salvaged.

12.3.2 Grubbing and Grading

All stumps and roots are removed from the ditch line and from all other right-of-way areas requiring grading. Grubbing is minimized at river or stream banks in order to maintain slope stability and reduce potential siltation.

Stumps and other debris are disposed of by burning or burial or by hauling to a disposal site, as required by landowners or authorities having jurisdiction.

Where grading of bedrock is required for right-of way preparation, rock is blasted using procedures outlined in Section 12.3.5 (Ditching).

The banks resulting from cut and fill operations must be sufficiently sloped or terraced to prevent injury to either people or livestock and to maintain natural drainage so as not to impound water on either side of the right-of-way. Grading the right-of-way to minimal side slopes provides a working area which reduces landing requirements and generally facilitates all phases of pipeline construction.

12.3.3 Handling, Hauling and Stringing

The source of materials and the prime mode of transport determines the location of stockpile and storage sites. Normally, pipe is delivered to selected rail sidings and forwarded by truck from these locations to the right-of-way.

Unloading, stockpiling, loading, hauling and stringing are done in a way which prevents denting, gouging, grooving or flattening of the pipe or damage to the external coating or to the pipe ends. Any tie-down chains and side pins should be adequately padded to eliminate rubbing. The front end of pipe loads moved by truck should be covered to prevent snow and or gravel from entering the pipes.

The pipe is strung on the right-of-way only after the clearing and grading operations are completed. Stringing should be done in a way that will prevent dirt, gravel, rock or other debris from entering the pipe.

Usually, openings are provided at approximately 450 m (1500 ft) intervals between the strung pipe to provide passage for vehicles, livestock and wildlife. Additional openings may be provided as required.

12.3.4 Topsoil Conservation

In many areas the landowners and or regulatory authorities require topsoil conservation. When equipment travel and pipeline operations would disturb the topsoil, it is advisable to strip topsoil for the entire width of the right-of-way. In other areas and for winter construction, conservation of the topsoil over the width of the ditch only will be sufficient. Figure 12-1 depicts the latter case.

12.3.5 Ditching

The pipe cover required will depend on the type of slurry to be pumped. Generally, water-based slurry lines require additional depth to prevent freezing. Where no frost problems are anticipated, the minimum figures given in Figure 12-1 will apply. Figure 12-1 also gives minimum width requirements for different pipe sizes. At locations where concrete river weights, saddle weights or appurtenances are to be installed, a trench sufficiently wide to permit installations should be provided. Saddle weights also require an extra 300 mm (1 ft) of ditch depth. At locations where the ground contour may vary due to approaches to roads, highways, railroads, ditches, streams and rivers, or where valve installations or underground line crossings are involved, additional depth should be provided to eliminate unnecessary bending of the pipe. At underground line crossings the ditch is excavated to a depth sufficient to provide a minimum of 300 mm (1 ft) of clearance while still maintaining minimum cover which generally requires the newer line to pass under the existing line(s).

Trenching may be performed before or after bending of the pipe. When done prior to bending, the pipe will be bent to fit the finished ditch bottom. When the ditching is done after bending, the bottom of the ditch will be cut to fit the bent pipe, and also maintain the required cover.

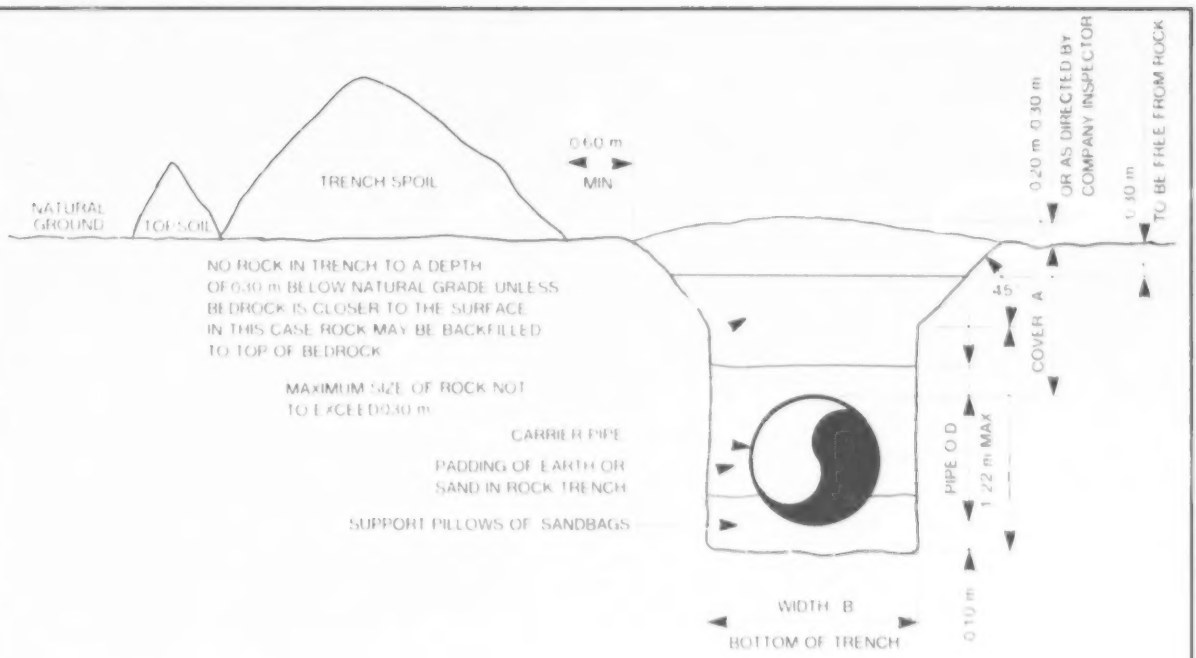
Where rock is encountered on the ditch line, a combination of blasting, ripping and backhoe excavation may be utilized in digging the ditch. Where rock ditch excavation is required, the ditch should be of sufficient depth to provide the required cover over the pipeline and an additional 100 mm (4 inches) for padding below the pipe.

All blasting should be done in accordance with the applicable regulations and good industry practice. In proximity of existing above or below ground facilities, additional restraints should be applied to ensure the security of such facilities. In developed farmland areas, particular care should be taken with backfill and clean-up operations to ensure that all blasted rock is removed and disposed of appropriately.

12.3.6 Bending

Generally, all bending is performed on the right-of-way by the cold stretch method with an approved bending machine. Fabricated bends may be used for special locations where field bending is not practical.

Bends should not be made nearer than 1.8 m (6ft) from the end of the pipe joint or closer than one pipe diameter from a girth weld for double-jointed pipe. Bending radius and out-of-roundness are subject to limitations specified in the applicable CSA pipeline code. (Refer to Chapter 16).


NATURAL GROUND
TOP SOIL
TRENCH SPOIL
0.60 m MIN
NO ROCK IN TRENCH TO A DEPTH OF 0.30 m BELOW NATURAL GRADE UNLESS BEDROCK IS CLOSER TO THE SURFACE IN THIS CASE ROCK MAY BE BACKFILLED TO TOP OF BEDROCK
MAXIMUM SIZE OF ROCK NOT TO EXCEED 0.30 m
CARRIER PIPE
PADDING OF EARTH OR SAND IN ROCK TRENCH
SUPPORT PILLOWS OF SANDBAGS
0.20 m 0.30 m OR AS DIRECTED BY COMPANY INSPECTOR
1.50 m TO BE FREE FROM ROCK
45°
COVER A
PIPE O.D
1.22 m MAX
0.10 m
WIDTH B
BOTTOM OF TRENCH

PIPE SIZE (O.D)	REQUIRED DIMENSIONS (METRES) FOR PIPE INSTALLATION IN							
	ALL TERRAIN COVER "A"		EARTH		ROCK		SWAMP	
			WIDTH "B" MIN.	DEPTH	WIDTH "B" MIN.	DEPTH	WIDTH "B" MIN.	DEPTH
610 mm	IN SOIL 0.75 m IN ROCK SEE CONTRACT DOCUMENTS		0.965 m	1.5 m	0.965 m	ADJUST TO SUIT PADDING AND COVER REQUIREMENTS	ADJUST TO ACCOMMODATE STYLE OF WEIGHTS USED	ADJUST TO PROVIDE NOT LESS THAN 0.90 m COVER PIPE
762 mm			1.118 m	1.7 m	1.118 m			
864 mm			1.219 m	1.9 m	1.219 m			
914 mm			1.270 m	1.8 m	1.270 m			

Figure 12.1 Ditch and backfill requirements

12.3.7 Welding

Welding may be done by a manual shielded metal-arc process using coated electrodes, a semi-automatic gas metal-arc and shielded metal-arc process, or automatic gas metal-arc process.

All welding done on the pipeline has to comply with the applicable pipeline regulations, and any supplementary requirements a company may determine during final design.

It is also a code requirement that welding procedure qualification and welder qualification tests are conducted prior to the start of production welding. Only welders who have been tested and qualified on the procedures and pipe used are permitted to weld on the system.

Production welding is performed using the welding process and procedures determined during the final design in accordance with the requirements of CSA Standard Z183-1982, Section 5.

12.3.8 Non-Destructive Testing

Radiographic inspection of all welds is becoming more and more the accepted practice for all larger diameter pipelines and in many cases is mandatory under the National Energy Board (NEB) pipeline regulations.

The requirements for acceptance and the repair procedures for welds which failed to qualify are specified in CSA Standard Z183-1982.

12.3.9 Pipe Coating

External pipe coatings are available from many manufacturers. Some are applied at the pipe mill or at a pipe coating plant prior to transportation to the construction site. Others are applied in the field by the construction contractor. Typical plant applied coatings are bonded epoxy film and extruded or wrapped PVC. "Over the ditch" applied coatings in common use are PVC tape and coal tar enamel and tape. Field applied coatings are installed after the pipe joints have been welded together and radiographic or other inspections of the weld area have been completed.

The welded joints of pipes with yard applied coating systems will be coated with similar materials in the field after the pipes have been welded and the welds inspected.

12.3.10 Internal Cleaning

After most of the pipeline has been installed, and before pressure testing begins, the sections of line (approximately 8 km (5 miles) in length) are internally cleaned and inspected.

These operations consist of running a number of cleaning scrapers through the pipe to ensure that loose debris and other materials accidentally left in the pipe are removed. Once the line is clean it is inspected internally by running an inspection pig to determine any out-of-roundness, dents or buckles in the pipe.

The inspection pig may be one of the several types available for that purpose in the industry.

Any unacceptable defects, as determined by criteria listed in the applicable sections of CSA Standard Z183-M1982, are corrected.

12.3.11 Water Crossings

Major and minor water crossings are treated in different ways.

Major water crossings are installed generally by special crews or specialist contractors following detailed procedures outlined in a site specific design for each crossing. Individual operations such as clearing approaches and welding could follow the procedures outlined in this Chapter, but others such as pipe handling, coating, and excavation would be selected to suit the particular crossing site.

Minor water crossings are treated as being part of normal mainline construction procedures and installed by regular pipeline crews.

When installing water crossings, care should be taken that environmental requirements regarding construction timing, prevention of siltation and contamination of the water, as outlined in Chapter 13, are strictly adhered to.

Generally, the pipe section to be placed in the crossing is made up and inspected prior to excavation and then placed into the excavated ditch which is then backfilled immediately.

Extra coating or other forms of protection may be used on pipe placed in minor water crossings as required.

12.3.12 Road and Rail Crossings

Railways, highways and other paved main roads are crossed by boring below them. In cases where boring is not possible due to presence of rock, special arrangements have to be made. These arrangements would depend on the type of crossing, rail or roadway and the traffic density. If no other alternatives are open, the crossing could be installed in a tunnel.

Crossings of unpaved and lightly travelled roads are generally made using the open-cut method.

The pipe to be installed in a crossing will be made up in sufficient length, provided with an extra thickness of external coating and be inspected prior to installation.

Upon completion of the boring or open-cut excavation, the pipe is placed in the crossing, supported where required and tied-in. Open-cut crossings are compacted in layers as the backfill is being placed.

12.3.13 Cleanup and Restoration

After the lowering-in and backfilling operations have been completed,the right-of-way and other areas disturbed by the construction activities will be cleaned up. Cleanup would generally follow the completion of backfilling as closely as practical but seasonal requirements for such items as seeding or revegetation may be delayed to the proper season.

The cleanup and restoration activities will restore the right-of-way to the original or better condition by replacing topsoil, cultivating, seeding of grass or other revegetation methods.

Boulders, brush, stumps, refuse and other waste material are disposed of in accordance with requirements stipulated by landowners or authorities having jurisdiction. In forested areas any leaning or otherwise seriously damaged trees on the edge of the right-of-way are felled and disposed.

Roads and fences damaged during the construction activities by removal of vegetation, grading or slope excavation, are restored and stabilized to prevent erosion and or slumping.

Various methods may be used to control erosion of the soil on the right-of-way, such as water bars, cross berms, contour furrows, water spreaders, diversion ditches, terraces and ditch plugs to distribute surface run-off, reduce its velocity and prevent ponding. Typical drawings for some of these measures are given in Figures 12-2 and 12-3.

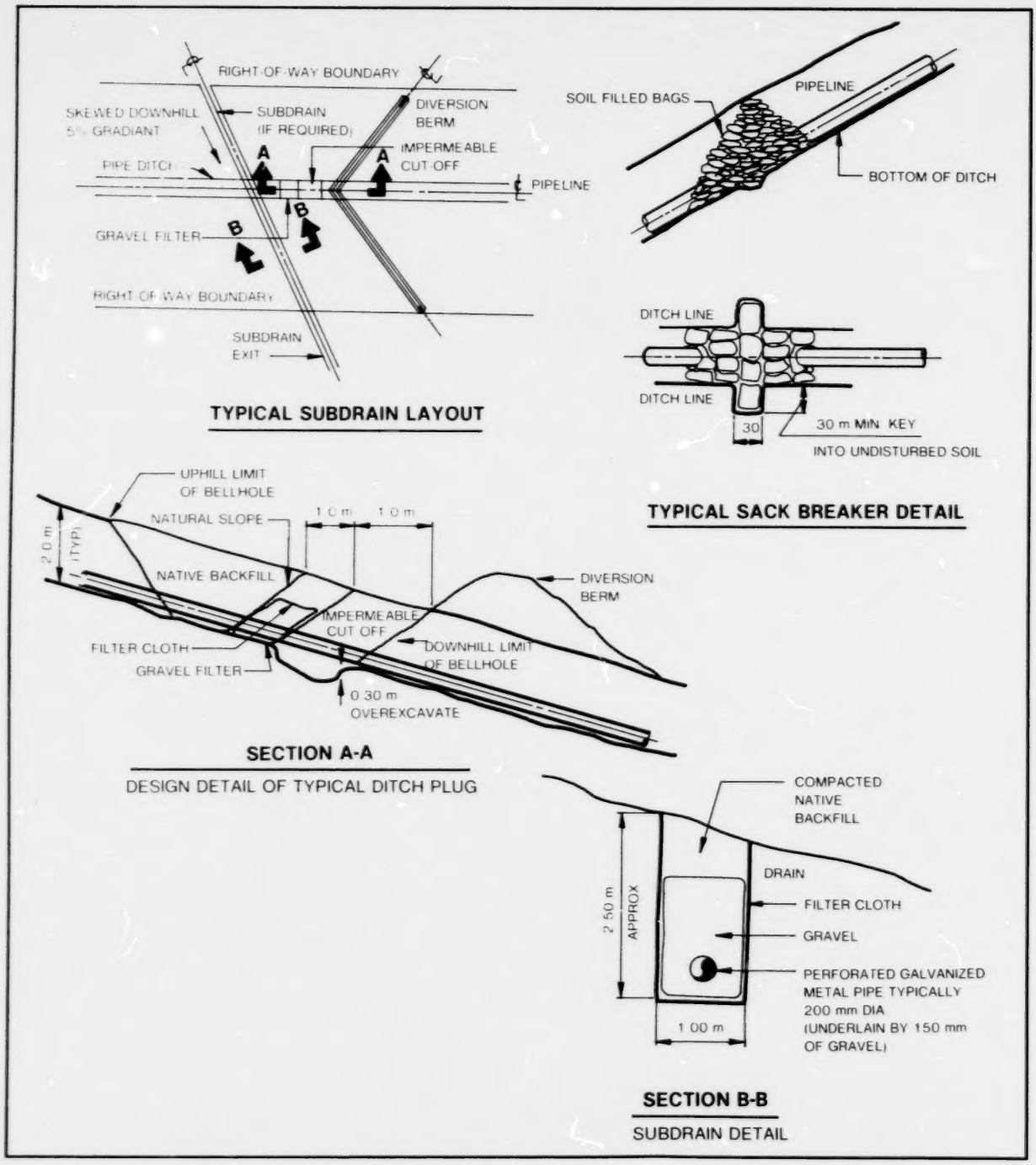


Figure 12.2 Typical sack breaker & sub drain system

Other areas not on the right-of-way and which have been disturbed by the construction, such as borrow pits and storage sites, are also restored to as near original conditions using the methods described above.

12.3.14 Pressure Testing

It is customary and in most cases mandatory under the requirements of the NEB and provincial authorities that pipelines are subjected to a pressure test prior to being commissioned.

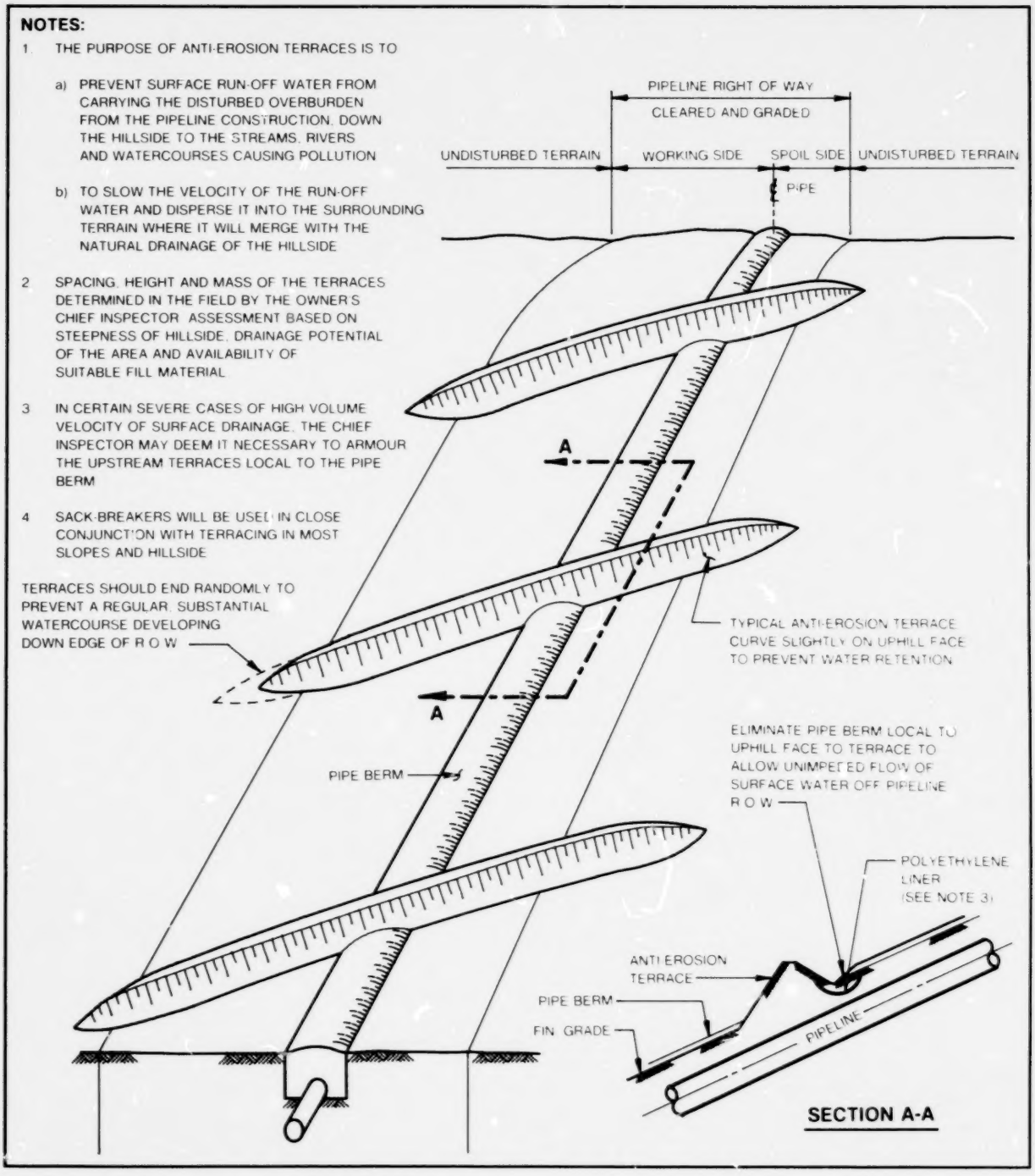

NOTES:
1. THE PURPOSE OF ANTI-EROSION TERRACES IS TO
a) PREVENT SURFACE RUN-OFF WATER FROM CARRYING THE DISTURBED OVERBURDEN FROM THE PIPELINE CONSTRUCTION, DOWN THE HILLSIDE TO THE STREAMS, RIVERS AND WATERCOURSES CAUSING POLLUTION
b) TO SLOW THE VELOCITY OF THE RUN-OFF WATER AND DISPERSE IT INTO THE SURROUNDING TERRAIN WHERE IT WILL MERGE WITH THE NATURAL DRAINAGE OF THE HILLSIDE
2. SPACING, HEIGHT AND MASS OF THE TERRACES DETERMINED IN THE FIELD BY THE OWNER'S CHIEF INSPECTOR. ASSESSMENT BASED ON STEEPNESS OF HILLSIDE, DRAINAGE POTENTIAL OF THE AREA AND AVAILABILITY OF SUITABLE FILL MATERIAL
3. IN CERTAIN SEVERE CASES OF HIGH VOLUME VELOCITY OF SURFACE DRAINAGE, THE CHIEF INSPECTOR MAY DEEM IT NECESSARY TO ARMOUR THE UPSTREAM TERRACES LOCAL TO THE PIPE BERM
4. SACK-BREAKERS WILL BE USED IN CLOSE CONJUNCTION WITH TERRACING IN MOST SLOPES AND HILLSIDE
TERRACES SHOULD END RANDOMLY TO PREVENT A REGULAR, SUBSTANTIAL WATERCOURSE DEVELOPING DOWN EDGE OF R.O.W.
PIPELINE RIGHT OF WAY
CLEARED AND GRADED
UNDISTURBED TERRAIN
WORKING SIDE
SPOIL SIDE
UNDISTURBED TERRAIN
PIPE
A
A
TYPICAL ANTI-EROSION TERRACE CURVE SLIGHTLY ON UPHILL FACE TO PREVENT WATER RETENTION
PIPE BERM
ELIMINATE PIPE BERM LOCAL TO UPHILL FACE TO TERRACE TO ALLOW UNIMPEDED FLOW OF SURFACE WATER OFF PIPELINE R.O.W.
POLYETHYLENE LINER (SEE NOTE 3)
ANTI-EROSION TERRACE
PIPE BERM
FIN. GRADE
PIPELINE
SECTION A-A

Figure 12.3 Typical erosion control terracing of slopes

The pressure test, in the majority of cases with liquid as test medium, is performed by the pipeline contractor under strict supervision of the owner's representative. Generally, a pipeline is tested in short segments as they are completed. The required test pressures, procedures and allowable operating pressures are specified in the applicable CSA Standards.

12.4 OTHER PIPELINE CONSTRUCTION MODES

12.4.1 Above Ground Construction

In cases where a pipeline crosses an area underlain by permafrost or where the frost penetration is deep enough, direct burial of the pipeline may not be a practical

solution. The Alyeska Pipeline is a well documented case where the pipe was installed above ground on special support piles. The pipe itself is covered with a suitable insulation and a protective sheet metal jacket.

Another alternative is to bury an insulated and heat traced pipeline. In permafrost areas this may cause environmental problems as it could cause degradation of the permafrost. In other areas this may be an alternative to having to install the pipe in excessively deep ditches.

Obviously the construction techniques for the above ground construction mode varies considerably from the direct burial mode, as there is no requirement for excavation and backfill. The general requirements for logistics, handling of the pipe and welding would be similar to those for a buried pipeline.

As the above ground construction mode has a very severe visual impact upon the terrain it crosses, considerably more than for an overhead power line, this method of construction should only be used when no other alternative could be used.

12.4.2 Submarine Pipelines

The subject of marine pipeline construction is not considered part of the scope of this manual. Any slurry pipeline to be installed in a marine environment would utilize one of the many existing construction techniques best suited to the requirements.

12.5 PLANT AND PUMP STATION CONSTRUCTION

The construction of slurry preparation plants, dewatering plants, storage facilities and pumping stations would follow standard practices for industrial construction and would conform to various codes and standards governing that type of construction.

12.5.1 Pumping Stations

Unlike pipeline construction which is a mobile operation, the station construction activities are limited to the selected site. Construction activities may take from 3 to 9 months depending on the type of equipment to be installed and time of year.

12.5.2 Preparation and Dewatering Facilities

Slurry preparation and dewatering facilities will generally be located on or adjacent to another industrial site, e.g., a mine, power plant or loading area. As the slurry preparation and dewatering equipment is much heavier and larger than the pumps and requires a greater amount of peripheral equipment, the construction activities are also of a greater magnitude and could take from 9 to 18 months to complete.

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13. ENVIRONMENTAL ASPECTS

by

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13.1 PURPOSE AND SCOPE

The purpose of this chapter is to identify the potential environmental implications of slurry pipeline construction, operation and maintenance. It also provides an assessment of some of the technologies and practices available to minimize the environmental effects of slurry pipeline construction and operation.

13.2 CONSTRUCTION IMPACTS

The terrestrial environment is affected by pipeline construction, as up to 2.5 ha (6.1 ac) per km (0.62 mi) of pipeline may be disturbed. Pipeline construction also will result in changes in the aquatic environment primarily as a result of erosion at stream crossings and along the right-of-way. The air quality will change during construction but these effects are usually minor and temporary. Modern construction and reclamation techniques ensure that most of the environmental impacts of pipeline construction are minimal and short-term. The capability of agricultural and forest land will, however, be reduced for longer periods.

13.2.1 Soils

There are three major concerns associated with pipeline construction and soils. These are topsoil loss, erosion and compaction.

a. A major impact, the loss or "dilution" of topsoil, may occur if topsoil is buried or mixed with subsoil during any of the construction activities. It is particularly important to replace topsoil if the subsoil has characteristics which adversely affect plant growth. Undesirable subsoils include highly alkaline, acidic, sodic or saline materials, poorly permeable materials (e.g., very high clay content), or excessively permeable materials (e.g., sands or gravels). Plant productivity will be reduced and in extreme cases plant growth may be severely inhibited if the topsoil is not replaced. Also, subsoil exposed at the surface is often more erodable than topsoil, particularly if the subsoil has poor structure and low infiltration characteristics.
b. Soils may be damaged by wind and water erosion during construction and before revegetation. Bare sandy soil is particularly susceptible to wind erosion during periods of low moisture. Depending upon soil type, moisture content and wind speed, several tonnes of soil may be lost per hectare per year (Ref. 1). These soil losses can reduce fertility, interfere with efforts to revegetate, and have adverse effects on nearby crops, water bodies and local air quality. However, depending on the soil structure, water erosion may be of greater concern. Heavy and intense rainstorms can wash away replaced topsoil exposing the less fertile subsoil. As a result of increased erosion, surface water quality decreases due to an increase in turbidity and total dissolved solids.
c. Compaction of soils by heavy machinery used in construction has adverse effects on the rooting environment of plants. The soil becomes less permeable, the water holding capacity and soil aeration are reduced, and in severe cases root development may be completely restricted by a compacted layer.

13.2.2 Slope Stability

Destabilization of a slope may result from the loss of support, an increase in weight and a change in shear strength usually as a result of the addition of water. Open trenches result in the loss of support and also intercept drainage, allowing materials not previously in contact with water to become wet and even water-logged. This can lead to landslides, rockslides, rockfalls and mud flows.

13.2.3 Vegetation

The loss of vegetation adversely affects soil because the exposed surface becomes vulnerable to erosion. Vegetative cover is important also because it provides wildlife habitat, commercial forest products, recreational sites, watershed regulation and because it has an aesthetic value. Habitat containing rare plant species may be destroyed if adequate precautions are not taken. In addition, there is an increased fire risk associated with pipeline construction. In farmland, there will be temporary crop loss and disruption of farming operations.

13.2.4 Wildlife

Animal populations will be displaced with the loss of vegetative cover. Major impacts can occur if the pipeline is constructed in areas used by wildlife during critical phases of their life cycle, e.g., ungulate winter range; calving areas; denning areas; important waterfowl breeding, feeding and staging areas; raptor nesting sites; and areas supporting rare and endangered species. Another effect of construction is harassment and disturbance caused by human presence. Most animals will move away from an area of construction but will return on completion of the project.

13.2.5 Biologically Sensitive Areas

Effects on biologically sensitive areas such as deserts and wetlands can be very severe as the ecological balance is often difficult and sometimes impossible to restore. Wetlands are particularly susceptible to the effect of construction as the associated plants and animals often have very specific requirements and even the normal annual cycle of changes in the hydrologic regime can alter substantially the characteristics of the wetlands.

13.2.6 Water

The major impact of pipeline construction on water quality is an increase in turbidity and sediment load in surface waters and an increase in turbidity and dissolved solids in aquifers. The factors responsible include run-off from eroded soils and underlying materials, construction activities at stream crossings, improper gradients and approaches at stream crossings which lead to erosion, and increased erosion from streambeds and banks due to loss of vegetation (Ref. 1). A change in water quality can alter the aquatic habitat and temporarily reduce species composition and productivity because of the reduction in dissolved oxygen and light. Water quality will continue to be affected until revegetation of the right-of-way is complete and erosion has ceased.

13.2.7 Air Quality

Increased fugitive dust and air emissions can arise from several sources. Trucks and construction equipment will cause dust and combustion emissions. Cleared areas and stockpiles of topsoil are prone to wind erosion and this will increase dust levels. Noise may be a factor in some areas.

13.3 MITIGATION

Conscientious planning, engineering design and common sense can minimize the impacts associated with pipeline construction (Ref. 2). In addition, environmental impact can be minimized by respecting the guidelines established by various govenment agencies which regulate pipeline construction. Specific mitigative measures will be required.

13.3.1 Soils

Topsoil must be conserved by stockpiling it separately from the subsoil. The use of topsoil for padding, roads and backfilling must be avoided to ensure that adequate topsoil will be available for replacement at the surface. Topsoil stockpiles should be treated so that erosion does not take place. This measure will not only conserve the topsoil but will reduce fugitive dust levels. Early re-vegetation is probably the best means of ensuring that topsoil erosion after reconstruction is reduced to a minimum.

Whenever possible wet soil conditions should be avoided as soils may compact severely if worked when too wet.

13.3.2 Slope Stability

Slope stability can be maintained by avoiding areas where:

a. there are signs of instability,
b. the underlying materials are clays, shales or siltstone,
c. the slope gradient is greater than 15°,
d. the trench cuts directly across the slope.

When the correct techniques are used in backfilling, the risks associated with slope instability are much reduced. The weight of the pipe will generally compensate for the weight lost due to the excavation of material (Ref. 1).

13.3.3 Vegetation

The effect of construction on the vegetation in forested areas can be reduced by clearing the minimum width required for construction, salvaging all merchantable timber, minimizing surface disturbances, disposing of slash and debris, and early revegetation. In farmland, construction in winter is preferred.

13.3.4 Wildlife

Careful scheduling of operations will result in the least environmental disturbance to critical wildlife habitats. Generally, depending on the species involved, the best times for construction are winter and mid-summer.

13.3.5 Biologically Sensitive Areas

By scheduling operation, generally in winter, environmental impacts will be minimized in biologically sensitive areas.

13.3.6 Water

Stream crossings are particularly sensitive to environmental degradation. Each stream crossing should be planned so that the trench is dug, the pipe lowered and the excavated material backfilled in one continuous operation. At sloping approaches to stream crossings, impermeable barriers should be constructed in the trench to prevent sediment flow into the stream. These barriers can be left in place after trench closure to reduce subsurface drainage which could lead to erosion within the trench, thereby threatening the integrity of the pipe. If reasonable care is taken, sedimentation and erosion of the stream and its banks can be kept to a minimum.

13.3.7 Air Quality

Dusting can be kept to a minimum by removing as little vegetation as possible and scheduling operations in winter.

13.4 Operation and Maintenance

Once all construction activities have been completed and the pipeline in operation, all environmental impacts of the slurry pipeline are greatly reduced. Only those which could not be mitigated in the construction phase still exist. Very few of these impacts are related directly to the pipeline and most arise from the interactions of the associated facilities with the environment.

The visual and noise impact of the pump stations and auxiliary facilities can be reduced if proper design and construction practices are followed (Ref. 3).

Operation of a pipeline will result in a slight increase in the emission of air pollutants. These pipeline caused emissions are a by-product of the generation of energy required to run the pump stations and other facilities and not a direct result of the pipeline itself. These emissions are unlikely, however, to result in a significant decline in ambient air quality.

In the event of a rupture of the pipeline, there would be a slurry spill. The amount of slurry released and the resulting environmental impacts depend on a number of factors such as the nature of the medium and solid, flow rate, pressure, burial depth, overburden density, and time for detection and automatic pipeline shutdown (Ref. 3). Emergency procedures involve dumping the slurry into ponds at pump stations. There are environmental impacts associated with such procedures including a possible seepage into the local groundwater supply, attraction of waterfowl to the pond and evaporation of the carrier to leave the fine material as dust. All these can be mitigated using appropriate technologies.

If water is used as the medium, the environmental impacts associated with its availability at the origin and its disposal at the destination have to be considered. The quantity of water required in a pipeline depends on two factors, the dry throughput requirement and the concentration of the solid in the slurry. The higher the water requirements are, the less desirable the system becomes. The two important factors to be considered at the origin are: surface waters may have prior commitments for agricultural, industrial or municipal uses, and environmental impacts may result due to the reduction in water volumes as fish and other aquatic biota may be affected. For these reasons groundwater may be the preferred source, but even then there will be environmental impacts associated with its use. The effects of groundwater pumping are difficult to determine and are unique to each aquifer. Most of these concerns relate to whether existing wells will need to be deepened and whether the quality of the water will deteriorate at greater depths. The important considerations at the destination mainly relate to how to dispose of the slurry water. The two alternatives most frequently proposed are to pump the water into existing surface waters or to use deep well disposal, or to use it on site (Ref. 2). In either case the water would require treatment so that it met the specified water quality standards and did not result in an environmental impact.

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14. PLANNING AND SCHEDULING

by

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14.1 INTRODUCTION

This chapter deals with the logistics considerations in conceiving, designing and constructing slurry pipeline systems. For major projects the logistic considerations are similar to those of any major cross-country pipeline system. For smaller projects and projects that are part of other facilities, the logistics considerations are intertwined with the overall facility and hence cannot be addresssed separately.

The remainder of this chapter discusses some of the planning and scheduling considerations that go into pipeline projects. This chapter then discusses construction planning and logistics considerations, transportation infrastructures and finally methods to put a pipeline system into operation.

14.2 Initial Planning and Permitting

Slurry pipeline projects, like most pipeline projects, begin with the need to transport a commodity from one point to another. Alternate forms of transportation are usually available and these must be compared to the unit transportation costs for pipeline systems.

The advantage of pipeline systems is their large carrying capacity with low costs. However, since they require substantial initial capital investment they are usually only feasible if the commodity to be transported must be done so in relatively large uniform volumes over many years of time. With such a scenario the cost of the system can be effectively amortized and the unit transportation costs kept low.

After the potential economic viability of a pipeline system has been established, pre-engineering studies are carried out to plan a conceptual pipeline system and to arrive at an anticipated unit transportation cost. For major projects, due to the requirement of amortizing the cost over a long period of time, long-term firm commitment contracts must be made for the transportation of commodities. To protect the public interests, regulatory bodies are generally established to oversee what is often termed as "public convenience and necessary". This means that the pipeline systems in return for their monopoly must serve the public good by providing the lowest unit transportation cost, with additional considerations for public safety and longer term social good. Chapter 16 on regulatory aspects outlines and discusses some of the regulatory bodies from which major pipeline projects have to seek approval.

If a project has been given regulatory approval it is deemed to be of benefit to all and therefore generally the regulatory bodies have the power of expropriating right-of-way from individual landowners who feel that the pipeline is not in their best interest. Pipeline companies usually make substantial efforts to arrive at a mutually acceptable right-of-way via crossing agreements with landowners. However, where an impass is reached on a long distance pipeline the power of expropriation may have to be applied and is an absolute necessity to allow projects to be constructed.

14.3 ENGINEERING AND PROJECT MANAGEMENT

After a permit to construct a pipeline has been obtained, a team of people must be assembled to manage the project. The major initial task is to complete the detailed engineering design and specifications for the pipeline.

Construction planning and approach is also an extremely important aspect for the management team to consider early in the project. Depending upon terrain conditions and pipeline lengths, construction may have to occur over a period of several years. In Canada in wet areas it normally is customary to construct the pipeline systems in the winter when the ground is frozen and can support heavy equipment. Another major consideration in construction planning is the availability and deliverability of the required pipe and equipment. Pipe mills generally custom roll large orders of pipe for major pipeline projects. Depending upon the level of general activity of the pipe mills, delivery times may vary from supply out of stock for very small projects to a requirement of several months to slot into the production schedule, with perhaps several months required to roll the pipe itself.

Another important function of the project management team is to control expenditures on the project. Usually elaborate computer-based systems are implemented to allow real time comparison of committed costs and actual costs to budgeted amounts for a wide variety of cost categories. On projects the term "committed costs" refers to actions and orders that are taken at a given point in time that will incur costs at some later date. This is very important as it may be the first indication of a project being overspent.

Major pipeline projects represent very large capital investments and when construction is underway the expenditures for pipe and construction may run at several million dollars a day. As a consequence errors in planning and management can result in very substantial cost overruns in relatively short periods of time. On the other hand, good project control and good luck can result in substantial savings. Plant construction generally proceeds at a slower pace and, although it is often more difficult to determine the committed level of expenditures, the project management team generally has more time to implement controls to rectify problems. In pipeline planning and construction it is critically important to get it right the first time.

14.4 TRANSPORTATION AND LOGISTICS

Upon completion of detailed design, purchase orders are placed for pipe and major equipment. In addition, construction specifications and contracts are completed. Bids are solicited from construction contractors to build the pipeline system. Since pipeline construction is a highly specialized process, construction contractors with "spreads" of specialized equipment undertake the construction of all aspects of a pipeline system. The one exception is that pump stations, meter stations and other buildings and facilities are usually constructed by more conventional contracting companies.

The main logistics considerations in constructing a pipeline are then the following:

a. providing material at the required point and time.
b. Having the equipment and all the necessary support at the right point and time.

These two considerations are discussed separately in the following sections.

14.4.1 Materials Logistics

In Canada, major pipe manufacturing facilities are located in Ontario, Saskatchewan and Alberta. In addition, pipe can be purchased from overseas sources but, in the interest of Canadian content and as prices are usually competitive, Canadian pipe tends to be purchased on major projects. The major item to be transported for any long distance pipeline system is the pipe itself. Other materials are transported by rail, truck or marine means as would be the case in any other facility construction. As pipe is bulky and heavy, long distance transportation on land is almost always done by rail. Sometimes, if rail transport is unavailable and if transportation by water is feasible, barges or ships are used. For international projects special ships exist which can transport large quantities of pipe as a single load.

Pipe is generally off-loaded at rail sidings onto trucks. As the timing of pipe delivery and need for pipe during construction are very difficult to synchronize, the pipe is usually kept at stockpile sites. These sites may be located along the right-of-way on property owned by the pipeline company or in industrial storage yards. From these points the pipe is picked up at the stringing stage of construction and delivered to the right-of-way, as discussed in Chapter 12.

In some instances, depending upon ground conditions or terrain obstacles, other vehicles such as low ground pressure or tracked vehicles or even helicopters are used to string the pipe. These methods are used only if there is no other means, as they are usually very costly.

14.4.2 Construction Equipment Logistics

The logistic support of the construction spreads consists of two main activities a) mobilization and demobilization of the construction spreads; b) operations and support of the spreads during construction.

Mobilization and demobilization consist of delivering all the large equipment to the construction point and at the end of the job returning it to its point of origin. As most of the equipment consists of heavy tracked equipment, it must be brought in by truck or rail to the starting point of construction activity. This is a major cost item in most projects and has a tendency of disporportionately increasing the unit construction cost of short distance, remotely located projects.

Once construction is in progress, both the equipment and the men working on the project have to be kept operational.

As far as the equipment is concerned, the biggest component required is fuel. Fuel is generally delivered or purchased at some common point and fuelling trucks move up and down the right-of-way fuelling the equipment. Other items such as lubricants and replacements also are required. An ongoing program of preventative maintenance and minor repairs is carried out along the right-of-way by specialized crews. Where major breakdowns occur or equipment becomes totally inoperable, replacement equipment must be brought in.

As far as the men are concerned on a construction spread, their biggest consumable is food. In remote locations construction camps are established at central points and men are bused to and from the construction points. For smaller jobs that are located near populated areas, construction crews can sometimes find accommodation in hotels, motels or boarding houses. More often today crews do not stay in towns because of the possible undesirable impact they may have on the communities.

14.5 CONSTRUCTION MANAGEMENT

A pipeline construction project can proceed as soon as the flow of material to the construction site has begun and the men are in place to do the work and are supported with equipment they require to function. Chapter 12 on construction discusses the various activities that are part of building a pipeline. Timing and management are very critical factors as a good, well supplied crew can lay several miles of pipe a day. Such a crew may consist of a large number of individual pieces of equipment and several hundred men.

The owner, or the project manager acting as the owner's agent, usually has construction inspectors oversee the contractor's field activities. This operation consists of a chief inspector having overall authority on the owner's behalf, with several specialty inspectors assuring quality on various activities of construction. On very large projects one or more inspectors can be assigned to each of the activities listed in Chapter 12. In addition, a specialized sub-contractor almost always is engaged to inspect some or all of the welds performed on the pipeline by radiographic, ultrasonic or other nondestructive testing methods. If welds are found defective, they must be repaired or redone.

In addition to the inspection of the activities on the right-of-way, the owner or project manager usually has materials personnel responsible for receiving, verifying and issuing materials to the construction contractor. Once materials are issued to the contractor, he must assume responsibility for their loss or damage.

14.6 TESTING AND COMMISSIONING

When the pipeline construction has been completed, it is tested prior to operation. Cleaning devices called pigs are run through the line using hydrostatic pressure to clean out any dirt or debris that may have been left in the line. The line then is tested hydrostatically with either water, water and methanol or other ice inhibiting agents, air or inert gases. The hydrostatic test consists of pressurizing the line to a pressure substantially above expected operating pressure but below, or at a maximum, the yield strength of the pipe. The pressure is held for some period of time to ensure that the line does not have any residual leaks.

Upon completion of the hydrotest, the testing medium is forced out of the line and in some instances batches of methanol or other drying fluid are run through the line to remove traces of the hydrostatic testing fluid.

Pump and metering stations and other facilities are tested and commissioned separately. In addition to hydrostatic testing of such facilities, commissioning usually consists of checking out all the electrical circuitry and instrumentation systems, operating all valves and safety devices and generally ensuring that all components of the system are functional and correct.

Once testing and commissioning are completed, the line can be turned over to the owner and put into service.

15. SLURRY PIPELINE COSTS

by

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15.1 INTRODUCTION

This chapter deals with the financial considerations involved in constructing and operating slurry pipelines. Like most facilities, costs associated with these systems fall into two general categories. The first is the capital or initial costs of the system and the second is the operating or continuing costs. The capital costs normally are amortized over the expected life of a project using appropriate financial parameters. The operating costs are incurred on a yearly basis and are charged directly to the overall costs of the system for the given year. For small systems or systems that are part of larger facilities, the capital and operating costs often are blended into the financial structure of the overall project.

The remaining sections of this chapter present some simple rules for estimating the capital costs of major slurry transportation systems. A discussion of the methods of computing operating costs follows. The implications of the capital and operating costs are discussed in the section regarding transportation unit costs. Finally, the example of a long distance pipeline presented in Appendix 8-2 of Chapter 8 is costed and discussed.

15.2 CAPITAL COSTS

Cost estimation of a proposed pipeline slurry system begins with a preliminary design and development of costs for the major elements of the proposed system. The costs of a typical slurry pipeline are broken into three con.ponents:

a. The slurry preparation facilities. These may include mines, crushing mills, sources of water and other facilities to prepare the slurry for pumping.
b. The pipeline system itself. In addition to the pipe it may also include initial and intermediate pumping facilities, storage facilities and operations and maintenance facilities.
c. The final component of the slurry system is the receiving facilities. These may consist of dewatering facilities, settling ponds, ship loading facilities or a variety of other components depending upon the particular slurry system to be considered.

With the wide variety of preparation and receiving facilities for various applications and slurry types, it is not possible to give rules of thumb to estimate the cost of these facilities. For relatively short slurry pipelines, these facilities may comprise the majority of the overall costs. However, for longer pipeline systems, i.e., 50 km or more, the cost of the pipeline system itself becomes a significant component.

This chapter will develop some rules of thumb and criteria to allow estimating longer distance slurry pipeline systems. For shorter systems, construction costs per unit length increase significantly due to the need to use more conventional earth moving and lifting equipment as opposed to the more highly specialized pipelining equipment.

15.2.1 Pipeline Costs

Slurry pipeline systems are not too different from conventional crude oil pipeline systems. Figure 15.1 illustrates a typical investment split for crude oil pipelines (Ref. 1). As can be seen from the chart, pump stations and equipment comprise about 18% of the total investment with miscellaneous facilities such as telecommunications and operation and maintenance facilities comprising around 8%. The remaining 70% or so is comprised of line pipe and fittings and pipeline construction. The pipeline construction is generally a little more than half of this amount.

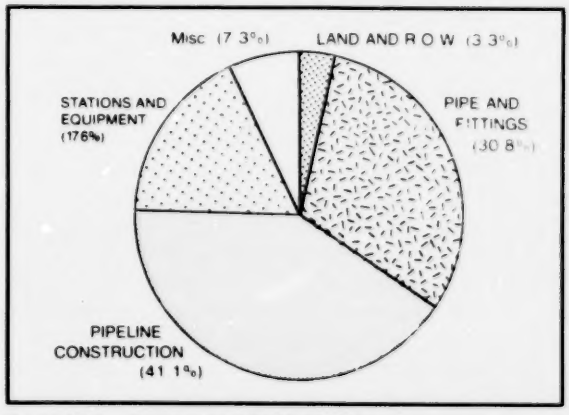

Figure 15-1. Investment split for pipelines

To estimate a slurry pipeline system, then, it is basically necessary to estimate the cost of pipe and fittings and pipeline construction. Allowances can be added for other facilities associated with a given pipeline. A useful reference for developing detailed pipeline costs estimates is "Cost Estimating Manual for Pipelines and Marine Structures" by J.S. Page (Ref. 2). Another useful reference is "Pipeline Construction Costs, 1975-1985" published by the National Energy Board (NEB) (Ref. 3).

The remaining sections of this chapter will develop the basis for estimating a slurry pipeline system. The costs that are presented are 1985 dollars. To convert to other years it has been found best to use the Oil and Gas Journal Morgan Oil Pipeline Cost Index published from time-to-time by the Oil and Gas Journal (Ref. 1).

15.2.2 Right-of-Way Costs

Table 15.1 presents estimated pipeline right-of-way or land costs for a range of pipeline systems. These estimates are based on rural land or crown land where easement costs would run about $750 an acre with damages and other costs running another $150 per acre.

It should also be noted that due to the requirements to construct the pipeline, larger diameter pipelines require a wider right-of-way.

15.2.3 Pipeline Material Costs

Table 15.2 presents dollars per tonne costs of steel at various grades for various pipe diameters. During the course of a design the pipe diameter and wall thickness are established. The formula following the table allows computation of pipe linear density. It should also be noted from the table that, in the larger diameter lines, higher yield strength steel is utilized. This is because the pipe wall thickness and the associated difficulty in manufacturing and field welding the pipe make it more economical to go to higher grades of material in these pipe sizes.

Table 15.3 gives some allowance figures for coating, valves and other material components. They are not generally very large numbers in the totals and hence a percentage approach is adequate to estimate these requirements.

15.2.4 Construction Costs

Construction costs are quite difficult to estimate as they depend very much on the type of terrain the pipeline is traversing. Table 15.4 presents pipeline construction costs for various line diameters and various types of terrain. Where a pipeline crosses differing terrain, these factors can be applied in segments to come up with an overall estimate of costs. However, where the pipeline system crosses major obstacles such as mountain slopes or major bodies of water the costs would have to be developed on a site-specific basis.

An additional 23% can be added to these costs to account for items such as field monitoring, fuel handling and storage, clearing and support facilities. Major river

TABLE 15.1
PIPELINE RIGHT-OF-WAY COSTS
$/metre

Pipe Diameter (mm)	R.O.W. Width			
	12 metres	15 metres	20 metres	25 metres
273 406	$2.68 m			
457 610		$3.34 m		
660 864			$4.45 m	
914 1219				$5.56 m

TABLE 15.2
LINE PIPE COSTS
$/TONNE

Pipe Diameter (mm)	Grade				
	X-42 290 kPa	X-46 317 kPa	X-52 359 kPa	X-60 414 kPa	X-65 448 kPa
273 406	$950 t	$1000 t	$1030 t	$1215 t	
457 610		$1050 t	$1100 t	$1150 t	$1200 t
660 864		$1010 t	$1030 t	$1080 t	$1130 t
914 1219			$1060 t	$1140 t	$1165 t

The above costs include 5% Federal Sales Tax.
Tonnage Calculation: LD = 0.02466 (D-t) t
LD = pipe density (kg metre)
D = outside diameter (mm)
t = wall thickness (mm)

TABLE 15.3
MISCELLANEOUS MATERIAL COSTS

(i)	Insulation*	$175 mm OD km
(ii)	External Coating	$35 mm OD km
(iii)	Swamp Weights	4% of line pipe
(iv)	Mainline Valves and Assembly	6% of line pipe
(v)	Transportation	Road $0.09, Rail $0.02, Barge $0.024 tonne km
(vi)	Provincial Sales Tax**	5% of line pipe
(vii)	Support Facilities Cost Storage Yards, Handling Equipment, Fuel Tanks and Other Facilities	5% of line pipe
(viii)	Miscellaneous Materials	4% of line pipe

* If required
**May vary according to province

TABLE 15.4
CONSTRUCTION COSTS
$/mm-km

Pipe Diameter (mm)	Base Prairie Cost ($/mm-km)	Terrain Multiplication Factor		
		Rock and Swamp	Mountain	Arctic
273 406	$125	x 3.0	x 3.2	x 3.5
457 610	$120	x 2.8	x 3.2	x 3.5
660 864	$128	x 2.7	x 3.2	x 3.5
914 1219	$144	x 2.7	x 3.2	x 3.5

crossings can be approximately estimated at $5,000 a metre for the overall river plus flood plain and river banks.

15.2.5 Pump Stations

The number of pump stations required is computed from the pressure drop of a given pipeline system. As a preliminary estimate, a pump station site without major storage tankage or other facilities could cost about $1.5 million with an additional $1,000 per installed kW of pump capacity.

15.2.6 Other Systems

In addition to the previous components of a pipeline, cost allowances have to be made for supervisory and control systems operations and maintenance facilities.

A typical supervisory and control system consists of micro-computer based station controllers with a central computerized monitoring and control system. Such a system would cost about $1.5 million with an additional allowance of $20,000 per station.

Operations and maintenance facilties for a new pipeline system can be about 2% of the overall capital cost. These facilities can vary widely, however, due to the operations and maintenance requirements of other parts of the overall project, e.g., a relatively short pipeline system associated with a major mining development might require very few operations and maintenance facilities over and above those necessary for the mine itself. This is also true of the supervisory and control systems.

15.2.7 Indirect Capital Costs and Contingencies

Considering the regulatory requirements described in Chapter 16 that need to be met to build a pipeline system today, and the engineering and construction management required, an additional allowance must be added to the cost of a pipeline system to take into account these requirements. A figure of 12% of the overall capital costs can be added to take into account permitting costs and engineering and construction management requirements.

Finally, some contingencies should be added to the overall estimate to take into account unforeseen factors and the possibilities of cost overruns. For a well defined project, a contingency of 10% can be used. However, if there are major uncertainties or the design is very preliminary, 20% is a reasonable contingency figure to use.

15.2.8 Summary

A preliminary estimate of pipeline system costs can be calculated utilizing the data given in previous sections and adding any necessary escalation. In doing a more detailed estimate, the same items that had been previously described have to be considered and their costs developed in a more detailed manner and with greater accuracy.

15.3 OPERATING COSTS

The operating costs of a typical long distance slurry pipeline system are made up of the following items:

a. energy costs,
b. operational and management staff payroll,
c. office and operations buildings, vehicles, maintenance equipment, consumables and spares,
d. property taxes,
e. insurance costs,
f. overhead costs and loss of product allowances.

15.3.1 Energy Costs

During preliminary design, the required horsepower and type of pump drivers are established. The common energy sources for pipeline pump drives are electricity, diesel fuel or natural gas. The specific driver fuel is determined on availability, reliability and economic considerations.

15.3.2 Operations and Management Staff

For a small pipeline or one that is part of a larger facility, the operations and management staff are usually not identified separately. However, for major pipeline systems, operating staff are required to operate the pump stations and measurement stations, maintain the right-of-way, repair equipment, check and calibrate equipment, and ensure overall safe operation of the system. In addition to the operations staff, there is a requirement for management staff to oversee the operation, and associated head office personnel to oversee administrative functions. The administrative functions would include items such as preparing billings to the users of the pipeline system, hiring operations and management staff, administering payroll and benefit plans, overseeing debt payment, dividends to shareholders, and other such corporate functions.

15.3.3 Facilities, Equipment and Consumables

Office and maintenance facilities and equipment are necessary to support the staff needed to operate the pipeline system. Facilities such as offices and shops that are constructed as part of the pipeline system usually are capitalized with the remainder of the system. In this case, the operating costs only consist of the utilities and upkeep costs of these buildings. Where buildings may be leased, the rental costs would be included in the operating costs. Consumables consist of items that are utilized in the operation of the system and include spares and replacement parts for items such as pumps, valves, and metering equipment.

15.3.4 Insurance

The following insurance coverages should be carried by pipeline companies:

a. automotive and aircraft liability insurance,
b. comprehensive general liability insurance,
c. course of construction liability insurance, if construction programs are carried on,

d. revenue interruption insurance.

With the ever increasing risks and liabilities of operating systems, other forms of insurance may be carried under specific circumstances.

15.3.5 Property Taxes

As a pipeline system generally represents significant property improvements and right-of-way, municipalities levy varying property and improvement taxes on the systems.

15.3.6 Overhead and Loss of Product

In addition to the specific items discussed above, pipeline companies generally add to the operating costs an allowance for other overhead items that may not be specifically identified. A major item in this designation is termed loss of product. Since modern pipeline systems do not have leaks on a continuing basis, this term applies more to inaccuracies in metering and material balance in the system over the course of a year. In slurry lines, leakage would become evident during normal inspection patrols and as a consequence, continuous small leakage would be highly unusual. However, this allowance is customary and would likely be levied on a new system.

15.4 UNIT TRANSPORTATION COSTS

15.4.1 Introduction

Having established the expected capital and operating costs of a particular slurry pipeline system, the unit transportation costs over the life of a project can be computed. In pipeline systems, this is referred to as the tariff or the cost of service. Since a significant number of financial variables are involved in unit transportation cost, only a general overview is presented here. The proceedings of the November 1982 conference dealing with "Pipeline Regulation and Inflation" (Ref. 4) presents some very comprehensive discussions of the impact of particular financial variables and assumptions on the computation of pipeline tariffs. In addition, this reference discusses the methods used by the NEB in establishing pipeline tariffs and is representative of the type of regulation that a major slurry pipeline project might experience.

In simple terms, the unit transportation costs or tariff are made up of an allowance for the following two components:

a. a capital related cost,
b. an operations related cost.

15.4.2 Capital Cost Transportation Component

When a pipeline system is constructed, the invested cost is carefully accumulated and capitalized. Depending on the regulatory regime,capitalization of certain expenditure items may not be allowed. Depending upon these restrictions, the final capitalized cost or rate base is established. The funding for a project is generally raised through equity and borrowing. The equity component may be a direct investment of another company or the proceeds of the sale of shares. The debt component may come from bank borrowings or the issuance of bonds, debentures, preferred shares or other debt instruments. The specific items making up this cost component are the following:

a. Book depreciation allowance based on depreciating the rate base of the system over the expected life of a project. This amount remains essentially constant from year to year.
b. Debt interest. This amount is the direct payment the company will make to pay for interest on debt incurred to construct the pipeline system. This amount decreases over the life of a project as the debt is repaid.
c. Return on equity. This is the amount of money that actually goes to the investor or the shareholders of the system. As this amount is paid out in dividends, after provision for taxes, the rate is usually specified on an after tax basis to assure that the amount actually is available to pay to the shareholders. Therefore, the anticipated tax that would be paid by the company on these amounts is collected as part of the tariff. As debt is repaid and the equity component of the system increases, this amount may rise over the life of a project. In addition, since the return to the shareholders has to be competitive with prevailing rates of return on other investments, this amount is adjusted from time to time, based on risk and prevailing interest rates.

15.4.3 Operating Cost Component

The operating cost contribution to the tariff is the exact amount of the operating costs discussed in Section 15.3. These costs are, of course, subject to inflation and will rise in absolute terms over the life of a project. In the later years of a project, they may greatly exceed the capital cost related component of the overall tariff. However, since the price of the transported commodity is also subject to inflation, it is often preferable to have increased operating expenses in the later years of a pipeline system, as opposed to making added initial capital investment.

15.5 CASE STUDY

To illustrate the preceding methods of establishing capital , operating and unit transportation costs, one of the examples presented in Chapter 8 is chosen. The case studies for the short mine tailings disposal line, Appendix 8-1, and the short pipeline for moving coarse particles, Appendix 8-3, would be best costed using conventional, mechanical and civil costing techniques such as presented in Reference 2. The case study for a long distance coal water slurry pipeline, Appendix 8-2, is chosen for detailed costing and evaluation. Although the specific

methods would differ for the other two cases, the general approach would be similar.

15.5.1 Capital Costs

The capital costs are computed in the following manner.

15.5.1.1 Right-of-Way. From Table 15.1 for 610 mm pipe diameter:

$$400 \text{ km} \times 1000 \frac{\text{m}}{\text{km}} \$3.34 \text{ m} = \$1,336,00.$$

15.5.1.2 Pipe Material. From Table 15.2, linear density is:

LD = 0.02466 (D-t)t
= 0.02466 (610 - 6.4) 6.4
= 95.26 kg m.

Required pipe tonnage is:

$$95.26 \frac{\text{kg}}{\text{m}} \times 400 \text{ km} \times 1000 \frac{\text{m}}{\text{km}} \times \frac{\text{tonne}}{1000 \text{ kg}}$$

= 38,105 tonnes.

From Table 15.2 for 610 mm, Grade 359 pipe, the cost is:

38,105 tonnes x $1,100 tonne = $41,916,000.

15.5.1.3 Miscellaneous Materials.

a) External Coating:
$35 mm OD km x 610 mm OD x 400 km
= $ 8,540,000.

b) Main Line Valves and Assemblies:
6% of $41,916,000 = $ 2,515,000.

c) Transportation: Assume trucking from Edmonton with an average haul of 150 km.

$0.09 tonne km x 38,105 tonnes x 150km
= $ 514,000.

d) Provincial Sales Tax:
5% of $41,916,000 = $ 2,096,000.

e) Support Facilities:
5% of $41,916,000 = $ 2,096,000.

f) Miscellaneous Materials:
4% of $41,916,000 = $ 1,677,000.

15.5.1.4 Construction Costs. From the route description of Appendix 8-2, about 50 km of the route traverses wet ground with the remaining 350 km being base prairie construction. Then from Table 15.4:

$$350\text{km at } \frac{\$120}{\text{mm-km}} \text{ for 610 mm pipe} = \$25,620,000.$$

$$50 \text{ km at } \frac{\$120 \times 2.8}{\text{mm-km}} \text{ for 610 mm pipe}$$

= $10,248,000.

Also, four major river crossings at an average width of 100 m each are:

4 x 100 m x $5,000 m = $ 2,000,000.

The TOTAL PIPELINE COST is the sum of items 1 to 4 = $98,558,000.

15.5.1.5 Pump Stations. The 6 pump stations can be approximately costed using allowances as follows:

6 x $1.5 million + 17,230 kw x $1,000 kw
= $26,230,000.

15.5.1.6 Other Systems.

a) SCADA

Assume this is a new, stand-alone operation, then:

$1.5 million + 6 x $20,000 = $ 1,620,000.

b) Operations and maintenance facilities.

Assume this is a new, stand-alone operation, then:

2% of ($98,558,000 + $26,230,000 + $1,620,000)
= $ 2,528,000.

15.5.1.7 Indirect Capital Costs and Contingencies.

12% of ($98,558,000 + $26,230,000 + $1,620,000 + $2,528,000) = $15,472,000.

TOTAL PROJECT CAPITAL COST
= $144,408,000.

15.5.2 Operating Costs

The operating cost components of the pipeline are computed as follows.

15.5.2.1 Energy Costs.

$$17,230 \text{ kw} \times 90\% \text{ availability} \times 8760 \frac{\text{hrs}}{\text{yr}} \times \$0.03 \text{ kwhr} = \$ 4,075,000.$$

15.5.2.2 Operations and Management Staff.

a) Operating, 40 @ $50,000 for payroll plus benefits = $ 2,000,000.
b) Management, 25 @ $50,000 for payroll plus benefits = $ 1,250,000.

15.5.2.3 Office, Vehicles and Consumables. Assume 1% of TOTAL PROJECT CAPITAL COST:

1% of $144,340,000 = $ 1,443,000.

15.5.2.4 Property Taxes. Assume 1% of TOTAL PROJECT CAPITAL COST:

1% of $144,340,000 = $ 1,443,000.

15.5.2.5 Insurance. For a system of this type, insurance coverage is found to be the following:

$200,000 + 1% PROJECT CAPITAL COST less PIPELINE COST

$200,000 + 1% ($144,408,000 98,558,000)
= $ 658,000.

15.5.2.6 Overhead Costs and Loss of Product Allowance.

Methods for computing these amounts vary, but let one assume = $ 750,000.

TOTAL YEARLY OPERATING COST = $11,619,000.

15.5.3 Unit Transportation Costs

As previously discussed the transportation cost (tariff) is made up of two components, the capital and operating costs. The capital cost must be amortized over the project life. The methods for doing this vary, but to illustrate, if the capital cost is amortized over 25 years at an interest rate of 12%, the yearly capital cost financing component is 12.4% of total capital cost.

For this example:

12.4% of $144,408,000 = $17,907,000.

The operating costs have already been computed on a yearly basis, so the total required yearly revenue is:

$17,907,000 + $11,619,000 = $29,526,000.

As the throughput is 10 million tonnes of coal annually, the unit transportation cost is:

$$\frac{\$29,526,000}{10,000,000 \text{ tonnes}} = \$2.95 \text{ tonne}$$

This figure is accurate for the first year of operation, because in later years the operating cost would be subject to inflation. However, since the cost of coal also might be subject to inflation, this first year transportation cost is useful in evaluating project viability.

15.6 REFERENCES

1. Oil and Gas Journal, OGJ - Morgan Pipeline Index - Oil, (2Q84 Cost Index) Pennwell Publishing Co., Tulsa, Oklahoma, February 25, 1985. pp. 92-4.
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3. National Energy Board Staff Study, "Pipeline Construction Costs, 1975-1985," Supply and Services Canada, June, 1982.
4. Morrison, R.N. and Schultz, R.J., "Pipeline Regulations and Inflation: An Evaluation of Tariff Levelling," McGill University, Montreal, Canada, 1983.

16. REGULATORY ASPECTS

by

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16.1 INTRODUCTION

Under the Canadian constitution the ownership of mineral resources and the rights to control and market them are vested in the provinces. The National Energy Board Act of 1959 grants the National Energy Board (NEB) wide power over the movement and marketing of energy and sources of energy when such movement and marketing activities involve export from one province to another or to a foreign country.

Although it may be difficult to forecast where the majority of slurry pipelines would be constructed, a reasonable assumption is that, as Canada is a country exporting vast quantities of natural resources, some of the major slurry pipelines would carry mineral resources across provincial and/or international boundaries. Smaller local lines may be carrying mine tailings to disposal sites or, as in Case 3 in Chapter 8, mined products to a railway loading site.

In the following sections the jurisdictions of the NEB, the Canadian Transport Commission (CTC) and provincial boards or other authorities will be examined.

16.2 FEDERAL AUTHORITIES

The NEB was instituted by an Act of Parliament in 1959 which has been updated and amended regularly since, with the latest revision in 1983. As quoted in Section 22 of Part II:

> The Board shall study and keep under review matters over which the Parliament of Canada has jurisdiction relating to the exploration for, production, recovery, manufacture, processing, transmission, transportation, distribution, sale, purchase, exchange and disposal of energy and sources of energy within and outside Canada, shall report thereon from time to time to the Minister and shall recommend to the Minister such measures within the jurisdiction of the Parliament of Canada as it considers necessary or advisable in the public interest for the control, supervision, conservation, use, marketing and development of energy and sources of energy.
>
> (Ref. 1).

In Part III a number of regulations are listed pertaining to the ownership, construction and operations of pipelines. However the definition of a pipeline as currently given in Section 2 (interpretation) states:

> "pipeline" means a line for the transmission of gas or oil connecting a province with any other or others of the provinces, or extending beyond the limits of a province or the offshore area as defined in Section 87, and includes all branches, extensions, tanks, reservoirs, storage facilities, pumps, racks, compressors, loading facilities, interstation systems of communication by telephone, telegraph or radio, and real and personal property and works connected therewith.
>
> (Ref.1).

In the same section it is stated that:

> "oil" means any hydrocarbon or mixture of hydrocarbons other than gas and includes any product designated as an oil product by regulations made under Section 89.
>
> (Ref. 1).

As such, "hydrocarbon" does not include coal, methanol, anhydrous ammonia, iron ore, sulphur, potash, potable water and many other commodities being transported or contemplated being transported by pipeline.

The NEB has consolidated the regulations for oil pipelines and gas pipelines into a new volume called "NEB Onshore Pipeline Regulations" (Ref. 3). Copies of these revised regulations have been sent to interested parties in the industry and comments have been invited. Until the new regulations are approved and published they are not binding.

The definition of "pipeline" in the new "NEB Onshore Pipeline Regulations" is the same as in the current oil and gas pipeline regulations so the new NEB does not regulate slurry pipelines, nor many other possible types of pipelines.

The regulatory aspects for pipelines located outside the provinces, i.e., the North West Territories and Yukon, and offshore pipelines are not clearly defined. The Canadian Oil and Gas Lands Administration (COGLA), a department of Canada Energy, Mines and Resources, has produced a set of draft regulations for pipelines and the NEB has also drafted regulations for offshore pipe-

lines. The definition of "pipeline" in both of these regulations refers only to oil and gas and thus only includes pipelines for the transmission of hydrocarbon gases and liquids.

The CTC is the federal agency having jurisdiction over bulk commodity transport by carriers under Federal jurisdiction. In so far as surface transport is concerned, CTC regulation has centered mainly on railway transportation. Jurisdiction over bulk commodity transport by pipeline also has been given to the CTC, in a sense, as a residual authority relative to the NEB jurisdiction, i.e., over any pipeline transmitting commodities other than those defined in Part II of the NEB Act.

Where there is a potential conflict, such as with slurry lines where the carrier fluid is a hydrocarbon, a decision would have to be made based on the primary purpose of the system. The current concensus is that jurisdiction would go to either the CTC or the NEB rather than having a split responsibility, even though joint jurisdiction is contemplated in the respective acts (NEB Act and National Transportation Act).

In the case of a coal-methanol slurry line, jurisdiction would go to the CTC, as methanol is an alcohol, not a hydrocarbon. Transporting a slurry in an existing system currently carrying oil and other hydrocarbons and under NEB jurisdiction would likely remain under NEB jurisdiction. That decision likely would be subject to legal argument.

To initiate the regulatory process the applicant(s) would have to apply to the appropriate regulatory bodies and submit, amongst information required by law for a certificate of public convenience and necessity as specified by those bodies, documentation to indicate that various authorities dealing with items such as river crossings, environmental concerns, wildlife refuges, national and provincial parks, highway and railway crossings and municipal concerns have been contacted and that the necessary permits have been obtained or agreements made.

16.3 PROVINCIAL REGULATORY AUTHORITIES

The provinces have instituted boards or commissions to exercise control over the exploration and development of their mineral and energy resources, which in many cases also includes the transportation by pipeline of gas, oil and related products. It may be beyond the scope of this manual to examine in detail the authority of each provincial board or conservation authority. It appears that currently the Alberta Energy Resources Conservation Board (ERCB) has more complete legislation in the energy field than the other provinces. The ERCB was given jurisdiction over pipelines by the Pipeline Act which was passed in 1975. Prior to this there was a pipeline licensing and inspection branch which operated independently from the ERCB. Unlike the NEB pipeline regulations, the Alberta Pipeline Act describes a pipeline as "a gas line, oil line, fluids line, multiphase line, solids line, secondary line, distributive line or flow line" (Ref. 2). Any slurry pipeline within Alberta jurisdiction would thus come under the ERCB regulations. It is anticipated that other provinces, if they have not already done so, would follow the same course.

16.4 UNITED STATES REGULATIONS

The regulatory aspects of U.S. pipelines and specifically for slurry pipelines are more complicated. Where state boundaries are crossed, approvals are required from both Federal and State agencies, sometimes with overlapping jurisdictions. R.M. Hartman and R.J. Cooper (Ref. 4) have written a paper describing some of the licensing problems and an analysis of the licensing effort for the Energy Transport Systems Inc. (ETSI) pipeline. The ETSI process was complicated by the fact that not only was the coal pipeline considered but also the much broader spectrum of issues such as water supply, coal preparation and mining operations and the power plants at the delivery points as well. Comparing the list of approximately 9 federal and state agencies involved in the regulatory process for the ETSI system with the outline of the regulatory process in Canada is "comparing apples with oranges" because for Canada (Sections 16.2 and 16.3) only the aspects of the pipeline itself were considered. The fact that the ETSI system eventually was cancelled was due partially to the fact that a federal judge ruled that the agency which had granted the water rights was not authorized to do so. The lack of eminent domain legislation in several of the states to be crossed, enabling the railroads to block the line at least for a considerable period by not granting the pipeline company permits to cross the railroad right-of-ways, was also a contributing factor.

As the ETSI line was to be only the second inter-state large coal slurry pipeline, the regulatory process was not clearly defined and the process has been educational for both the industry and the legislators. Current moves are under way to streamline the process for any future application.

16.5 CODES AND STANDARDS

The regulatory bodies described in the earlier parts of this chapter generally adopt the relevant national standards for design of pipeline systems as the minimum design criteria to be met as part of the regulatory process. One notable exception is the NEB which in its "Regulations Respecting Oil Pipelines" and equivalent for gas pipelines has sometimes adopted requirements which are different from those specified in the relevant Canadian Standards Association (CSA) codes. As part of the ongoing process of consultation between the NEB, CSA and the pipeline industry, proposals are being made to have the NEB regulations refer to the applicable CSA standards, either by year and issue or "latest editions", to avoid the overlapping and sometimes contradicting

requirements. Currently there is no CSA standard for slurry pipelines although a subcommittee was instituted late in 1984 to commence work on a slurry pipeline code (refer to Chapter 11).

Should an application be made for a slurry pipeline to an appropriate regulatory body at this time or prior to the completion and adoption of a slurry pipeline code by CSA, the body would have the option to use CSA Z183, or possibly modify the requirements in line with the new U.S. American National Standards Institute (ANSI) 31.11 slurry pipeline code (due to be released late in 1986).

16.6 PERMIT APPLICATIONS

An application for a permit to construct a slurry pipeline under federal jurisdiction would be made to the CTC. To date only two applications for pipelines have been made. As these are for high pressure steam, it is difficult to predict what the exact criteria would be to deal with such an application, but in all likelihood the procedure would be as previously established by the CTC for the steam line applications. The first step in the approvals process would be to apply for a "certificate of public convenience and necessity". If it is deemed in the public interest, often determined by public hearings wherein interested parties are permitted to intervene, and the certificate is granted, a company may then proceed with detailed design, right-of-way acquisitions, etc. and apply for "leave to construct". After examination and possible input from interested parties, the design and route would be approved and the line and facilities constructed. Upon completion of the construction and acceptance of testing, the company would apply for "leave to open" which, when granted, would permit a company to put the facilities in operation.

The provincial process, although the terminology is somewhat different, follows more or less the same procedure.

In both cases the hearings into the public convenience and necessity aspect of the project would look into the economic viability of the system, to determine if the proposed project would be viable, and the financial stability of the applicant, as well as related safety aspects.

Apart from engineering aspects, it is anticipated that, under the current CTC regulatory regime, the economic aspects of a slurry pipeline application would be dealt with in a manner similar to the way the CTC deals with railway rates. One controversial issue centres on tariff regulation of a slurry pipeline. The current NEB system allows for a tariff structure which is quite high in the earlier years of the project and then diminishes as the debt component reduces with age. This method of computation has a tendency to make projects uncompetitive in the earlier years of the project life. Another method which has been advocated for oil and gas pipelines is a system where the tariff is based on a weighted average annual return, where the tariff starts low and increases with the inflation rate, thus keeping the transportation charges at a more even ratio of the total commodity cost. It should be noted that there is a marked difference between the NEB and the CTC in regards to their policy and procedures approach. The railways, regulated by provisions of the Railway Act and the National Transportation Act which are administered by the CTC, are obliged to charge at minimum a "compensatory" tariff for transportation services (i.e., the long run variable cost). Railway rates are filed with the CTC but are not regulated. Should a slurry pipeline be proposed which could be deemed to be in competition with a railway operation, "unfair competition" could be claimed if the pipeline tariff was computed using a weighted average tariff. In the event that a company applying for a certificate to transport a commodity by pipeline has agreements regarding volumes and tariffs in place with the user(s), the regulatory authority may be required to convene hearings when interveners opposing the system emerged. The "compensatory" tariff issue could become very important in the event that competing systems were considered.

16.7 REFERENCES

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2. Pipeline Act, Alberta, 1975.
3. National Energy Board Part VII Regulations, 1983.
4. Hartman, R.M. and Cooper, R.J., *Proc. Sixth International Technical Conference on Slurry Transportation*. Las Vegas, U.S.A., 1981, p 291.

17. RESEARCH AND DEVELOPMENT

by

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17.1 DISCUSSION

Slurry transport requires further development. Areas in which efforts should be directed are:

1. hydraulic studies of systems with interesting properties,
2. modelling and associated experimental measurements designed to elucidate mechanisms,
3. commercial scale studies of slurries of industrial importance, using a range of pipe sizes,
4. rheology of mixtures, including particle size distribution and surface property effects,
5. instrument development,
6. pump hydraulic performance (efficiency and derating) studies, including modelling,
7. wear studies (erosion and erosion with corrosion),
8. particle degradation during transport,
9. ancillary transport system studies including coal cleaning and slurry dewatering.

The first area is probably the most important because it provides the stimulus for new applications or mechanistic research. For example, this area includes such diverse studies as the effect of additives, pipe materials of construction or free surface (open channel) flows. Naturally, a complete specification of suitable investigations for such curiosity-based effort is impossible. However, it is likely to remain the most important type of research activity for years to come.

Mechanistic modelling is necessary to provide a structure within which experimental observations fit. It is useful also for predictions in hypothetical situations of commercial interest. However, convincing models require experimental studies, often of an idealized nature, so that their assumptions and simplifications can be verified and improved. Like the exploratory work of the previous category, these mechanistic studies can be conducted with equipment of modest scale and are suited for university research.

In addition to small scale mechanistic research, a data base of industrial importance provides a test for modelling efforts. This data base should be carefully documented and employ a range of pipe sizes of commercial scale. Although studies of this type have been conducted in the past, it has been noted elsewhere that deficiencies exist in the case of homogeneous and near-homogeneous turbulent and transition flows of non-Newtonian slurries. Similarly, the effect of fines content in mixtures with broad particle size distributions needs systematic study. In addition to their value in modelling, these studies are also useful guides to industrial feasibility studies by demonstrating what can be achieved with existing technology.

Although systematic rheological investigations have been conducted, there is still a large unexplored area. This work is essential for modelling and can be of considerable value in qualitative interpretation of the interesting or industrially-important phenomena noted in areas 1 and 3. This work does require fairly expensive instrumentation for rheology, particle size, shape and surface property investigations, however.

There is a continuing need for new instruments for slurry concentration and on-line particle size determinations. Reliable devices for velocity measurement exist for most practical situations except laminar flows of slurries with negligible electrical conductivity. New methods would be useful in these areas.

In view of the dominant industrial importance of centrifugal pumps, it is surprising that a systematic study of the effects of rheology, particle size and concentration on their performance still is required. Such a study should have a substantial theoretical component and internal measurements of concentration and velocity would be necessary. Again, this is a suitable field for academic research.

Wear processes are of immeasurable importance and remain topics of great industrial interest. Because of substantial research in this general area for many years, the mechanisms are reasonably clear. However, particle trajectories for slurries have been ignored in most wear studies, although photographic techniques to study these are available. Such studies of particle motion near an abraded surface would perhaps help to resolve the controversies in the literature. Wear in pumps has recently been studied (Ref. 1) in parallel with particle trajectory predictions, with encouraging results for this approach. Certainly, new experimental techniques are

required, including rapid simulations of abrasive pipe wear (erosion and erosion-assisted corrosion).

Particle degradation during transport has been studied in recirculating loops for which pump effects are likely to be dominant. However, pipeline flow degradation is still primarily a subject of conjecture. This is probably one area in which field measurements with an operating pipeline, such as that in a coal cleaning plant, would be useful. Such studies should be part of a program to design a simulation procedure for particle degradation.

Finally, since pipelines are sometimes only one component of a transport system, research is desirable to clarify the effects of pipeline variables (rheology, particle size distribution) on the other operations which comprise the transport system. Only in this way can the competing requirements of the components be analyzed rationally.

17.2 REFERENCES

1. Roco, M.C., Nair, P., Addie, G.R. and Dennis, J., *Proc. Symp. on Liquid-Solid Flows and Erosion Wear in Industrial Equipment*. A.S.M.E., 1984. p. 69.

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